

**EXPERIMENTAL STUDY OF EARTH PRESSURES
ON RETAINING STRUCTURES**

by

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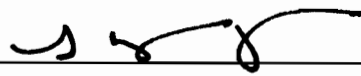
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Civil Engineering

(ABSTRACT)

Previous laboratory and field experimental studies of earth pressures exerted on retaining structures and laboratory studies of the at-rest earth pressure coefficient are summarized. The current methods used to evaluate the earth pressures due to compaction are reviewed.

The design features of a new instrumented oedometer developed to investigate the effect of number of load cycles on the at-rest earth-pressure coefficient are presented along with the results of a series of tests on Monterey sand #0/30.

The Instrumented Retaining Wall Facility developed to provide a means of obtaining experimental measurements of the earth pressures exerted on retaining structures is described. The instrumented wall of the facility is seven feet high and ten feet long and is instrumented to measure horizontal and vertical forces, horizontal earth pressures, horizontal deformations, and temperature. A description of the microcomputer-based data-acquisition system and the software used to record the test results is included.

The results of four tests where Yatesville silty sand was compacted in layers in the Instrumented Retaining Wall Facility are presented.

The experimental results are compared with the results of similar studies by others and to an analytical method used to estimate compaction-induced earth pressures.

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CHAPTER 1

INTRODUCTION

The design of earth retaining structures was among the earliest reported applications of engineering principles to soil mechanics. Rational methods for the design of earth retaining structures date back to Gautier (1717), who proposed a method for proportioning gravity retaining structures (Skempton, 1979). The works of Coulomb (1776) and Rankine (1856) provide the basis for our current understanding of lateral earth pressures on retaining structures.

The problem of lateral earth pressure on retaining structures has been the focus of numerous experimental investigations. Early investigations focused on determining the lateral thrust exerted on the retaining structure and its point of application. More recent studies have included the evaluation of the effects of wall movements, water pressures, backfill properties, construction procedures, and other factors on the magnitude and location of the resultant force vector and the distribution of earth pressures on the structure. Feld(1940) contains a review of early experimental works on earth pressures and a bibliography for the period from 1720 to 1940.

An understanding of earth pressures and their distribution has application to a variety of geotechnical engineering problems. The most evident of these is the interaction between a retaining structure and the backfill, where it is important to be able to evaluate the lateral

pressure and the vertical shear force on the retaining structure. Other problems where knowledge of the lateral soil stresses is useful include: hydraulic separation and hydraulic fracturing in earth dams, analytical modeling of earth structures, evaluation of the earthquake resistance of earth structures, soil-structure interaction studies, and analyses of reinforced earth systems.

Despite the large number of investigations into the nature of earth pressures, there remains a need for additional information from carefully controlled experimental investigations. Additional information is needed to confirm earlier work and to provide a bases for the formulation and validation of new analytical methods, particularly those dealing with specific aspects of the earth pressure problem. This need for experimental information relating to earth pressures has inspired the current investigation.

The purpose of this study is to investigate the factors that influence the earth pressures on retaining structures. The primary objectives are to: 1) review reports of experimental studies of earth pressures on retaining structures, 2) review reports of laboratory studies of the at-rest earth pressure coefficient, 3) review the current methods of analysis for compaction-induced earth pressures, 4) develop and test an instrumented oedometer, 5) develop and test an instrumented retaining wall facility, and 6) compare the experimental results obtained from the new instrumented retaining wall facility to those of earlier studies and to current analytical methods.

Chapter 2 contains a review of the experimental investigations reported in the literature beginning about 1920. Included in the review are reports of field instrumentation programs, model wall studies, and laboratory studies of the at-rest lateral earth pressure coefficient, K_0 . The previous studies are summarized in a series of tables. Each table is followed by more detailed review of several selected studies. Reports of experimental investigations prior to those reported here (about 1920) are summarized by Feld (1940).

It is well recognized that compaction of soil increases the lateral stress in the soil and that a portion of that stress increase remains after compaction. A review of the current methods for evaluating the lateral earth pressures due to compaction is contained in Chapter 3. The analytical methods proposed by Broms (1971) and by Duncan and Seed (1986) are reviewed.

The instrumented oedometer developed during this investigation to study the at-rest lateral earth-pressure coefficient is described in Chapter 4. The instrumented oedometer was used to investigate the effect of repeated load cycles on the relationship between the horizontal and vertical stresses for Monterey sand #0/30. Test results are presented and evaluated.

Chapter 5 contains a description of the Instrumented Retaining Wall Facility developed during this study. Development of this facility and the initial tests performed in it represent the major effort of this study. The facility has a 10 ft. long by 6 ft. wide by 7 ft. high main test area with a 12 ft. ramp at one end for access to the test area.

The instrumented wall is 10 ft. long by 7 ft. high and consists four panels. Each panel is 2.5 ft. wide by 7 ft. high. The four wall panels are supported horizontally and vertically by load cells and can be moved as a unit by a steel frame and jack system. The wall movements can be rotational, translational, or a combination of these. Instrumentation includes three types of earth pressure cells, vertical and horizontal force transducers, displacement transducers, distance sensors, and thermocouples. A total of 64 instruments are monitored by a microcomputer-based data-acquisition system controlled by software written during this study. The calibration procedures and data-acquisition system are also discussed in this chapter.

The first series of tests in the Instrumented Retaining Wall Facility were performed using a silty sand from Yatesville Dam in Kentucky. Chapter 6 describes the engineering properties of the silty sand, the test procedure, and the test results. Data from the tests are compared to the results of similar investigations reported in the literature and to analytical methods.

Chapter 7 contains conclusions based on the performance evaluation of the instrumented oedometer and the instrumented retaining wall facility. Recommendations for future studies are included.

CHAPTER 2

REVIEW OF EARTH PRESSURE STUDIES

2.1 INTRODUCTION

Previous experimental earth pressure studies have been reviewed and these studies are summarized in this chapter. The review included field and laboratory investigations of earth pressures on retaining structures, and laboratory studies of the at-rest lateral earth pressure coefficient, K_0 . The summary is arranged in three main sections in the following pages: 1) Field Studies, where the earth pressure instrumentation program was a secondary objective, 2) Model Wall Studies, where the primary objective was to gather experimental earth pressure data, and 3) Laboratory K_0 Studies concerned with investigation of the effects of overconsolidation and cyclic loading on the value of K_0 .

2.2 FIELD STUDIES

More than two dozen experimental field studies of earth pressures on structures were reviewed. The structures include retaining walls, basement walls, bridge abutments, navigation locks, a concrete box culvert, an underground power house, and a concrete dam.

Table 2.1 contains a summary of these studies. Each entry in the table includes the source of the information, a description of the

Table 2.1) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
Goldbeck, A. T. 1938	Three bridge abutments: a) 30 ft. high, backfilled with clay-sand-gravel, b) dimensions and fill material not specified, and c) 32 ft. high x 24 ft. wide U-type, backfill material type not reported	Pressure cells were used to measure lateral earth pressures. Primary findings were: a) observed pressures corresponded to the pressure of a 48 pcf fluid, backfill was heavily compacted and outward wall movements of about 2 in. were measured at the top of the wall; b) fill was placed loose, pressure measurements corresponded to the pressure of a 33 pcf fluid; and c) fill was compacted in 12 in. lifts, measured pressures were influenced by precipitation and seemed to be influenced by the proximity of weep holes in the wall, pressures corresponded to those of a fluid weighing 23 to 41 pcf.
Sowers, G. F., 1957 Robb, A. D., Mullis, C. H., and Glenn, A. H.	6 ft. high retaining wall backfilled with clay.	Lateral pressures for compacted backfills were higher than those for uncompact backfill. The measured residual stresses for compacted backfills were, in general, greater than the calculated K_0 stresses. pp
Sims, F. A., 1970 Forrester, G. R., and Jones, C. J. F.	40 ft. high x 30 ft. wide section of a 1500 ft long wall that varied in height from 24 to 42 ft., backfilled with conditioned hopper ash, $\phi' = 21^\circ$ to 30° , $c_u = 0.0$	Earth pressure cells, placed about 2 ft. from the wall, were used to measure vertical and horizontal pressures. Strain gages were incorporated into the concrete wall, near the front and back faces. The average horizontal and vertical pressures increased steadily with time during the 20 month observation period. An increase in lateral pressure was also indicated by the strain readings of the concrete wall.
Brons, B. B. 1971 and Inge' lson, I.	10 ft. high bridge abutment, backfilled with uniform sand, $D_{10} = 0.32$ to 0.38 mm, $\phi' = 33^\circ$.	The fill was compacted in layers by a 3.8 ton vibratory roller. At shallow depths (up to 2 ft.), K was greater than 1.0 and in some cases approached K_p . Measurements were influenced by wall movements resulting from temperature changes in the bridge slab.

Table 2.1 Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Corbett, D. A., 1971 Coyle, H. M., Bartoskewitz, R. E., and Milberger, L. J.</p>	<p>18.5 ft. high retaining wall supported by piling and a 2.25 ft. thick pile cap (test wall D), backfilled with poorly graded sand (SP), authors estimated $\phi' = 32^\circ$.</p>	<p>The fill was placed in layers and compacted by scraper traffic and approximately three passes of a bulldozer. Compacted lifts were about 8 in. thick. The primary objective was to evaluate four types of earth pressure cells for future use. Calibration method, effect of temperature changes on the calibration factor, and drift of the zero reading with time and with changes in temperature were found to be important factors.</p>
<p>Broms, B. B. 1972 and Ingelsson, I.</p>	<p>9 m high bridge abutment backfilled with well graded sandy gravel to 6 m and uniform sand above 6 m</p>	<p>Backfill was placed in 60 cm thick lifts and compacted with a 3 ton vibratory roller. A 140 kg vibratory plate compactor was used near the wall and between the vertical ribs. K, based on measured pressures, was about 0.4. Observations over a period of about 2.6 years indicated large seasonal fluctuations in the measured pressures as well as daily fluctuations caused by temperature changes in the bridge slab.</p>
<p>Coyle, H. M., 1972 Bartoskewitz, R. E., and Milberger, L. J.</p>	<p>30 ft. long retaining wall supported by piling and a 2.25 ft. thick pile cap, wall height varied and was 16 ft. at the instrumented section (test wall G); backfilled material was SP-SM, $\phi' = 32^\circ$.</p>	<p>Continuation of work reported by Corbett, et al. (1971), on test wall D, revealed that several instruments in that study had a significant shift in zero reading. For test wall G, fill was placed in layers and compacted by scraper traffic and approximately three passes of a bulldozer to a thickness of about 8 in. For the upper 7 ft. of the wall, measured pressures were close to those calculated using $K_0 = (1 - \sin \phi')$. Below this depth, the measured pressures were greater than those calculated for the K_0 case.</p>

Table 2.1 (Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
Clausen, C. J. F. 1972 and Johansen, S.	2.35 m long x 2.05 m high wooden formwork basement wall, backfill is sand near the wall and clay beyond the sand	No compaction was used during fill placement. After compaction the lateral resultant force on the wall was about 0.5 ton/m and increased to about 1.0 ton/m over a period of about three months, then remained relatively constant for the remaining seven months of the study. The earth pressure coefficient, based on an assumed unit weight for the backfill and the lateral force of 1.0 ton/m, was reported as 0.28.
Kany, M. 1972	30 m diameter cylindrical structure, height of instrumented section was about 26 m, backfilled with gravel and cobbles; $D_{10} \approx 2$ mm and $D_{60} \approx 75$ mm	The structure was instrumented with earth pressure cells and an instrumented panel to measure shear stress. Measured earth pressures were generally at-rest pressures or greater, with some measurements approaching the passive pressure condition. After construction the shear force on the instrumented panel corresponded to a mobilized interface friction angle of about 20° .
Vaughan, P. R. 1972 and Kennard, M. F.	Junction between an embankment dam and a concrete dam; interface height of about 25 m, embankment material was boulder clay, average undrained shear strength was 74 kN/m^2 .	The embankment material was compacted in 150 mm thick layers. At the end of construction, total stress σ_H/σ_V values ranged from 0.67 to 0.72 for the four cells on the end face of the concrete dam. One pressure cell, on the upstream face of the concrete dam, indicated a total stress σ_H/σ_V of 0.32. After construction, the lateral pressures decreased slightly with time.
Prescott, D. M., 1973 Coyle, H. M., Bartoskewitz, R. E., and Milberger, L. J.	Precast retaining wall, instrumented panel is 10 ft. 8 in. long x 9 ft. 10 in. high, supported on pilasters founded on drilled piers, backfilled with sand (SP-SM), $\phi' = 32^\circ$ from direct shear tests	The measured earth pressure was near the active earth pressure in the upper two-thirds of the wall but approached the at-rest pressure near the bottom of the wall. Total thrust measurements agreed with the integrated pressure cell readings. Wall deflections were translational and rotational. The value of Δ/H at the top of the wall was 0.007.

Table 2.1 (Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Coyle, H. M., 1974 Bartoskewitz, R. E., Milberger, L. J., and Butler, H. D.</p>	<p>Test wall G, as reported by Coyle, et al. (1972)</p>	<p>Continuation of the test wall G study reported by Coyle, et al. (1972) with additional data and similar conclusions.</p>
<p>Jones, C. J. F. P. 1975 and Sims, F. A.</p>	<p>Four bridge abutments with wing walls, sand backfill</p>	<p>Measured pressures were higher than active pressures predicted by Coulomb's theory. The higher pressures were attributed to the stiffness of the structures and the residual stresses caused by compaction. Three-dimensional finite element analyses were used to calculate the earth pressures. It was concluded that the three-dimensional effects are significant for this type of structure. The finite element analyses did not include compaction effects.</p>
<p>Coyle, H. M. 1976 and Bartoskewitz, R. E.</p>	<p>Same wall as Prescott, et al. (1973)</p>	<p>Continuation of the study reported by Prescott, et al. (1973). Additional test results were reported with similar conclusions.</p>
<p>Coyle, H. M. 1977 and Bartoskewitz, R. E.</p>	<p>Same retaining walls as Coyle and Bartoskewitz (1976) and Coyle, et al. (1974)</p>	<p>Continuation of the study of two instrumented retaining walls. In both cases the walls continued to yield slowly, at a rate of $\Delta/H = 0.0007$ to 0.0010 per year. The measured earth pressures fluctuated seasonally.</p>
<p>Nielson, F. D. 1977</p>	<p>34 ft. high and 50 ft. high retaining structures, tiered arrangement using precast concrete units</p>	<p>A total of 88 pressure cells on the two walls indicated that the pressure distribution on this type of structure is very complex. In general the measured pressures were below those calculated using Rankine's earth pressure theory.</p>

Table 2.1 Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Ingold, T. S. 1979</p>	<p>230 ft. long cantilever retaining wall, wall stem heights of 17.4 ft. and 24.3 ft., backfill was 2 ft. below top of wall; fill in front was 12.4 ft. lower; backfill was very silty slightly sandy clay and gravel, $\phi' = 35^\circ$, $c' = 0$, $\gamma = 135$ pcf, $\delta' = 32^\circ$.</p>	<p>The fill was compacted in 1.3 ft. thick lifts by a vibratory roller with an equivalent weight of 66 kN, corresponding to a line load of 47.8 kN/m. The top of the wall deflected 3.7 in. by the time backfill placement and compaction had been completed. The deflection corresponds to $\Delta/H = 0.013$. Excavation of the backfill revealed a horizontal tension crack in the wall stem near its base. Initial design did not consider compaction induced stresses.</p>
<p>Roth, W. H., Lee, K. L., and Crandall, L. 1979</p>	<p>Two sections of a basement wall, one 34.4 m high and the other 31.3 m high, backfill at both locations consisted of a 0.5 cm thick corrugated cardboard filled with dry bentonite placed against the wall, 1 cm of soft fiber-board, 90 cm of pea gravel, and compacted silty sand beyond the pea gravel</p>	<p>Earth pressure cells were monitored during construction and observed pressure increases corresponded with the progression of the backfilling. The pressures during and after construction corresponded to a lateral earth pressure coefficient ranging from 0.18 to 0.24. Test results were compared to earth pressures calculated using the finite element method. Calculated pressures were sensitive to selected Poisson's ratio and the assumed value of the soil-wall interface friction angle.</p>
<p>Schulze, L. W., Coyle, H. M., and Bartoskewitz, R. E. 1981</p>	<p>184 ft. long retaining wall ranging in height from 2 to 11.5 ft.; instrumented section was about 11 ft. high, backfilled with impervious clay to 1.5 ft. above the top of the footing, remainder of backfill was SP-SM material, $\phi' = 34^\circ$ to 43°, $C_u = 2.45$, $C_c = 1.53$</p>	<p>The clay and sand fill within 3 ft. of the wall were compacted, in 6 in. compacted lifts, by a vibratory compactor. The sand fill beyond 3 ft. of the wall was compacted, in 6 in. compacted lifts, by approximately 3 passes of a bulldozer. Density measurements indicated a wide range of densities. The horizontal thrust resultant calculated from pressure measurements was about 3.5 times larger than that calculated using Culmann's graphical procedure. The vertical force resultant on the base of the footing, calculated from the pressure measurements, was about 80 to 90 percent of the expected value.</p>

Table 2.1 (Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>1983 Bruner, R. F., Coyle, H. M., and Bartoskewitz, R. E.</p>	<p>14 ft. high section of a 382.5 ft. long cantilever retaining wall, backfilled with high plasticity clay (CH), $c_u = 1900$ to 3000 psf</p>	<p>The clay was compacted behind the retaining wall. The pressures after construction corresponded to an earth pressure coefficient of about 1 in the upper 9 ft. of the fill. The measured pressures were essentially constant from 9 ft. to 13 ft. and decreased slightly between the depths of 13 ft. and 14.5 ft. Twenty months after construction, the measured movement at the top of the wall was about 1.7 in. ($\Delta/H = 0.01$).</p>
<p>1984 Fukuoka, M and Imamura, Y.</p>	<p>11 m long x 7 m high retaining wall, two instrumented panels totaled 2 m long x 6 m high, backfilled with poorly graded gravel with sand (GP)</p>	<p>The measured vertical resultant force was as high as 30 to 50 percent of the measured horizontal resultant force. Both force resultants increased in magnitude with time. The increases were attributed to the influence of rainfall on the soil properties, and other factors.</p>
<p>1986 Vogt, N, Chara, G, Hilmer, K, Nowack, F, and Grimm, G</p>	<p>25 m high lock wall, backfilled with compacted sand</p>	<p>Measurements of horizontal earth pressures and wall deflections indicated that the earth pressures fluctuate seasonally and with the operating cycle of the lock. Measurements indicated that the mobilized wall friction angle fluctuate between 22° and 42° during an observation period of more than 5 years.</p>
<p>1987 James R. W. and Brown, D. E.</p>	<p>8 ft. x 8 ft. x 44 ft. long box culvert, SC-SP backfill, $c' = 0$, $\phi' = 31.8^\circ$</p>	<p>Measurements were made of the earth pressure on a box culvert due to surface applied vehicle loads with different depths of cover. The authors suggested empirical scaling factors for use with theoretical lateral stress distribution equations for depths of cover up to four feet. They also proposed an empirical equation for calculation of lateral stresses for depths of cover greater than four feet.</p>

Table 2.1 Cont.) Summary of Experimental Investigations of Earth Pressures - Field Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>McCann, A. J., 1987 McIlwrath, J. C., and Stuart, J. G.</p>	<p>1 km long x 8.5 m high retaining wall, backfilled with 100 mm crushed stone; $\phi' = 37.5^\circ$ and $\gamma = 19 \text{ kN/m}^3$ were assumed for the design</p>	<p>Measured lateral pressures after construction corresponded well with those calculated using $K_0 = (1 - \sin \phi')$. Measured deflections indicated $\Delta \approx 7 \text{ mm}$ at the top of the wall at the end of construction ($\Delta/H = 0.0008$). Unexpected compressive strains were measured on the top of the heel and in the upper part of the wall on the backfill side.</p>
<p>Murray, R., 1987 Symons, I., and Farrar, D.</p>	<p>Two bridge abutments: a) 7 m high, backfilled with well graded sandy gravel, $\phi' = 48^\circ$ from shear box tests on samples with the coarse fraction removed, avg. $\gamma = 2.27 \text{ Mg/m}^3$, and b) 11.3 m high, backfilled with pulverized fly ash, $\gamma_d = 1.06$ to 1.1 Mg/m^3</p>	<p>Both abutments were instrumented with earth pressure cells. In both cases, long term observations indicated that the measured pressures were influenced by seasonal temperature changes. Measurements of vertical pressures for the 7 m high wall indicated that the vertical pressure above the heel was higher, and that measured above a point beyond the heel was lower, than the calculated overburden pressure. This difference in vertical pressure was also indicated by finite element analyses.</p>

structure and the backfill material, and a summary of the principal studies and findings.

Several of these studies are reviewed in greater detail in the following sections. Each investigation reviewed in detail was chosen for one or more of the following reasons: 1) it represented a pioneering effort to obtain field earth pressure measurements, 2) it involved a specific type of structure, other than a conventional retaining wall, or 3) it provided exceptionally well-documented evidence relating to compaction-induced pressures, pressure changes with time and/or temperature, or soil-backfill interface shear stresses.

2.2.1 Goldbeck (1938)

Goldbeck, in 1913, while working for the Test Division of the Office of Public Roads and Rural Engineering, took on the task of investigating the distribution of pressures due to concentrated loads. The first phase of this work involved the development of an instrument to measure earth pressure. Several earth pressure cells were tested and evaluated. The final design was judged suitable for measuring earth pressures on retaining walls and later became known as the Goldbeck earth pressure cell.

Several of these pressure cells were installed on the abutments of three bridges: 1) Sixteenth Street Bridge, Washington, DC, 2) Bennings Bridge, Washington, DC, and 3) Skellit Fork Bridge, Illinois. Only the Sixteenth Street and the Skellit Fork bridges will be discussed, because

the information reported for the Bennings Bridge was too limited to be of value.

A cross section of the Sixteenth Street Bridge and the pressures recorded during the study are shown in Figure 2.1. The abutment is 34 feet high, from the base of the footing to the top of the abutment. The backfill is a clay-sand-silt mixture and was compacted in three-inch-thick horizontal lifts.

The measured pressures indicate an almost linear increase in pressure with depth, except for the readings of pressure cell number 1. Cell number 1 was located one foot above the top of the footing and it is likely that arching within the backfill reduced the pressure near this pressure cell. The readings of cells number 2 and 3, on December 20, are inconsistent with the other readings for these two cells and with the expected pressure distribution. The remaining observations indicate that the pressures fluctuate over a narrow range. The measured pressures can be approximated by the pressure of a fluid with a unit weight of 48 pounds per cubic foot.

The earth pressures on the Skellit Fork Bridge were measured by twelve Goldbeck pressure cells, arranged with two cells at each of six elevations. The cells were mounted with their pressure sensing faces flush with the concrete surface of the abutment. The abutment was designed for the pressure of a fluid weighing 21 pounds per cubic foot. The instrumentation program was prompted by the fact that similar abutments, designed for the same fluid pressure, showed signs of distress.

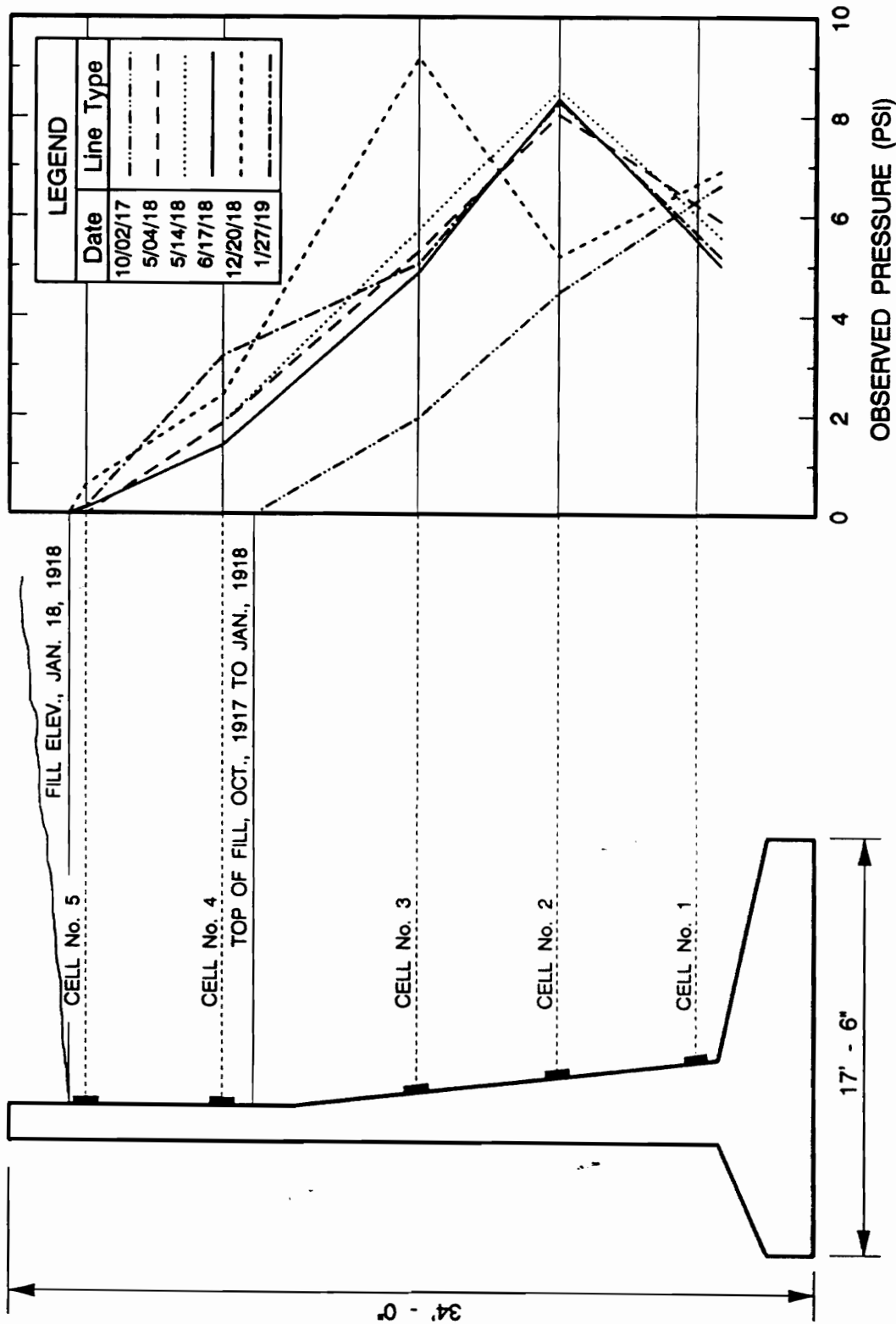


Figure 2.1) Measured Earth Pressures, Sixteenth Street Bridge, Washington, DC (after Goldbeck, 1938).

The measured pressures at the six instrument elevations are shown in Figure 2.2. Goldbeck suggested that the irregular variation of pressure with depth may have been caused by an irregular distribution of water pressure on the wall. The abutment has weep holes at three elevations, as indicated in Figure 2.2. The water pressure, and thus the total pressure, would be lower in the vicinity of the weep holes. The pressure cells with readings lower than expected are located closest to the weep holes. The measured pressures were also reported to have been affected by rainfall. The pressures increased during, and shortly after, rainy periods and were lowest at the end of extended dry periods.

2.2.2 Broms and Ingelson (1971)

Broms and Ingelson (1971) instrumented an abutment of a 500-foot-long rigid-frame bridge. Displacement and earth pressure measurements were recorded during and after construction. The 94-foot-long by 10-foot-high front face of the abutment supports one end of the bridge and is hinged at the top and bottom. The bottom of the abutment is supported by a foundation slab and four concrete piers that extend to bedrock. A change of 50° F in the temperature of the bridge deck will cause its length to change by 1.2 inches if the deck is unrestrained. One-half of this movement, applied at the top of the abutment, corresponds to a rotation of 0.005 radians. For the compacted backfill, a rotation of 0.005 radians toward the backfill was expected to produce lateral pressures approaching those of the Rankine passive case.

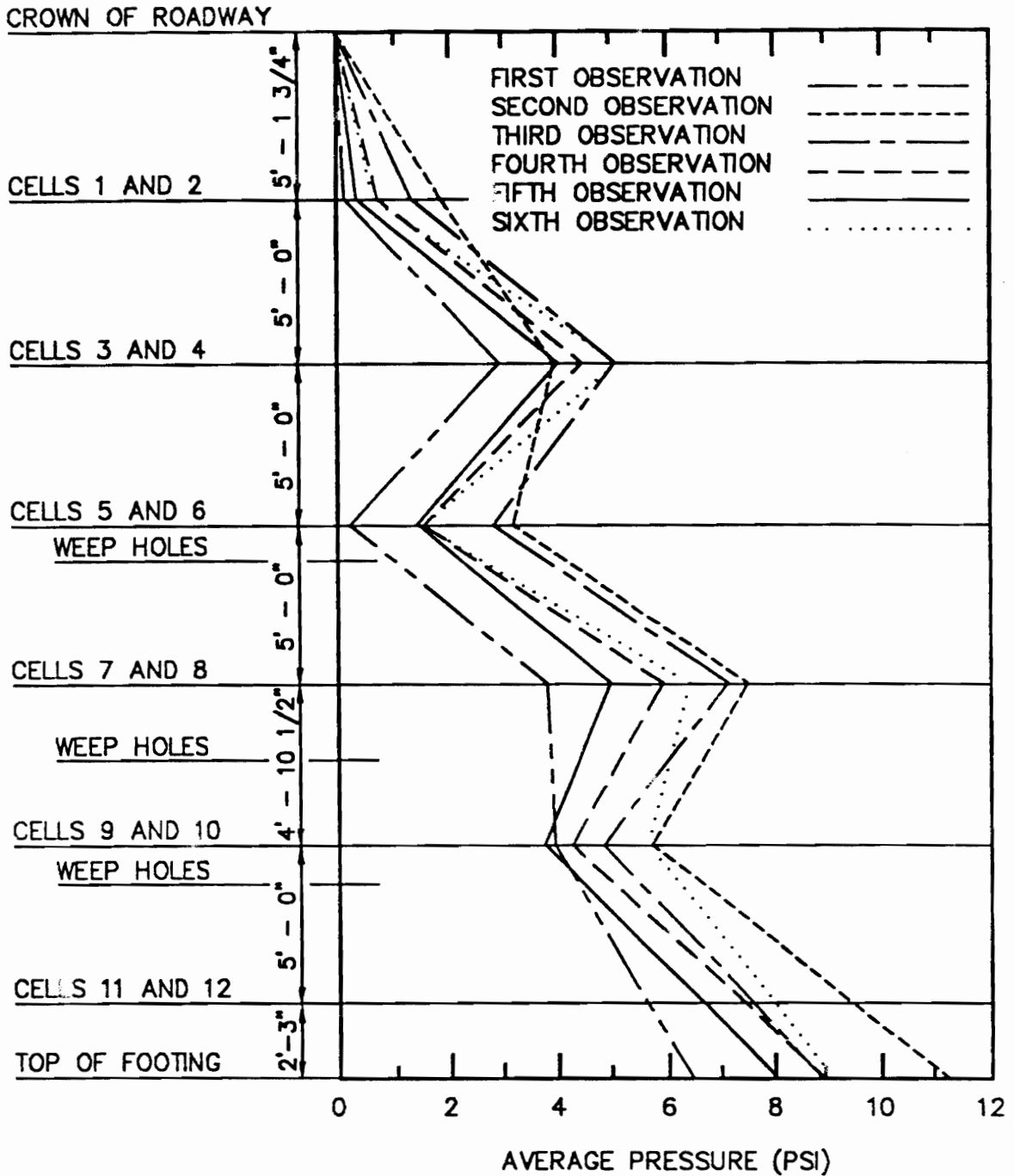


Figure 2.2) Measured Earth Pressures, Skellit Fork Bridge, Illinois (Goldbeck, 1938).

Therefore, the abutment was designed for the Rankine passive earth pressure loading.

The backfill was a uniform sand with $D_{10} \approx 0.33$ mm, $D_{60} \approx 0.60$ mm, and $C_u \approx 1.8$. Based on drained direct shear tests, the relationship $\tan \phi' = 0.385/e$ was determined for the sand. The average compacted dry density was 104 lbs/ft³ with a corresponding internal friction angle of 33°. During construction the fill was placed in 20-inch-thick layers and compacted by a 3.8-ton vibratory roller, except near the abutment, where a 660-pound vibratory compactor was used.

Eight earth pressure cells were installed in two vertical lines. One group was centered on the east half of the abutment and the other group was centered on the west half. Two reference beams and a caliper were used to measure the displacements of the abutment. The reference beams were cast into the foundation slab and were considered to be fixed. The measured pressures and displacements for the west section are shown in Figure 2.3 and those for the east section are shown in Figure 2.4. The pressure distributions corresponding to the Rankine active and passive cases are shown in Figures 2.3 and 2.4 for reference.

The measured pressures vary over a wide range. Pressure measurements from the upper three cells at both locations indicate pressures ranging from near those of the Rankine active case to greater than those of the Rankine passive case. The pressure distributions labeled A in the two figures correspond to the earth pressures at the end of construction. The upper two pressure readings, at both locations, indicate that the earth pressures at the end of construction

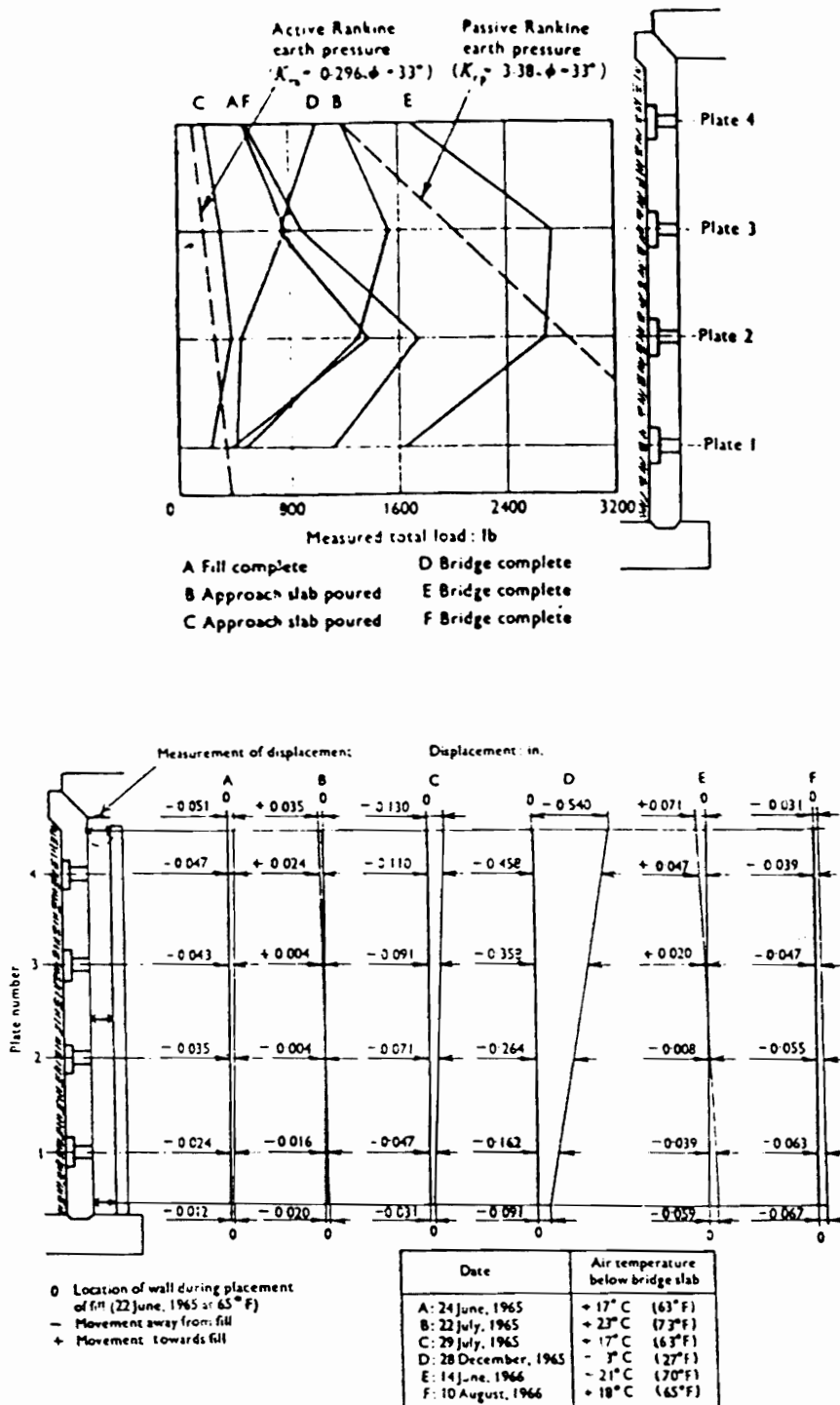


Figure 2.3) Measured Load Distribution and Wall Displacements of the East Section (Broms and Ingelson, 1971).

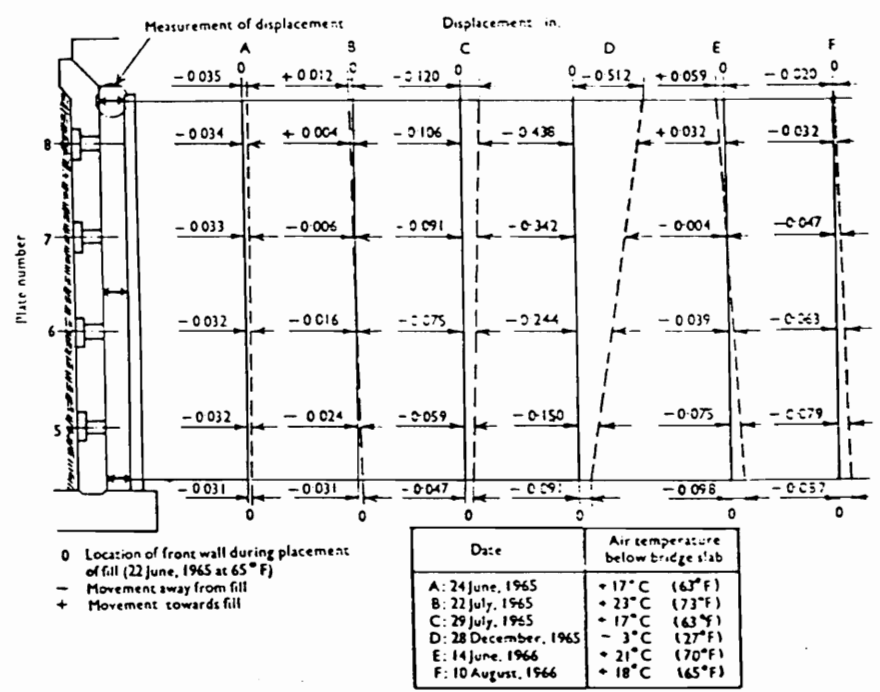
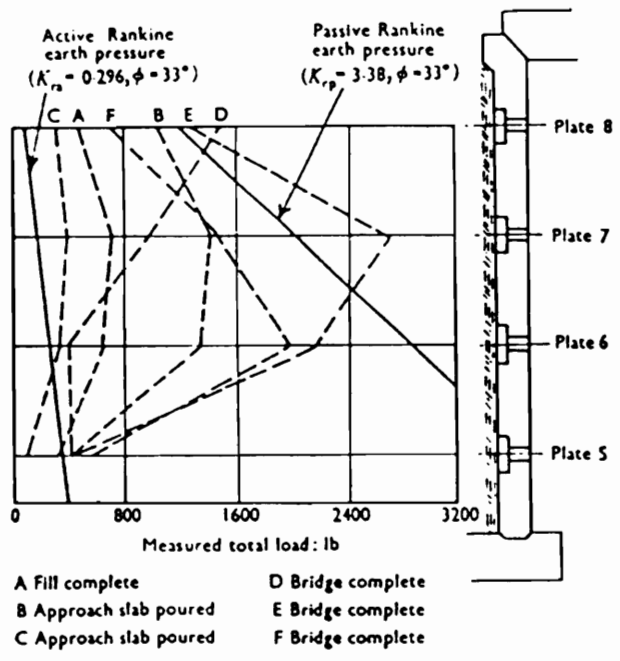


Figure 2.4) Measured Load Distribution and Wall Displacements of the West Section (Broms and Ingelson, 1971).

were more than twice those calculated for the at-rest case using $K_0 = 1 - \sin \phi'$. The lower two pressure cells, at both locations, indicate uniform or decreasing pressure with increasing depth. The higher-than- K_0 pressures in the upper portion of the fill at the end of construction are probably due to residual compaction stresses. The lower pressures observed in the bottom of the fill may be the result of the wall yielding slightly as the upper layers of the fill were placed and compacted.

The displacement measurements indicate that the wall movements can generally be characterized as rotation about the base. The influence of thermal expansion and contraction of the bridge deck on the wall movements can be inferred from the temperature records given with the displacement measurements. For all of the reported cases, an increase in temperature was accompanied by wall movements toward the backfill and a decrease in temperature was accompanied by wall movements away from the backfill. In general, wall movements toward the backfill correspond to increases in pressure and wall movements away from the backfill correspond to lower pressures, as expected. Exceptions to this are the pressures labeled D in Figures 2.3 and 2.4. The backfill was reported to have been partly frozen when these readings were taken.

2.2.3 Vaughan and Kennard (1972)

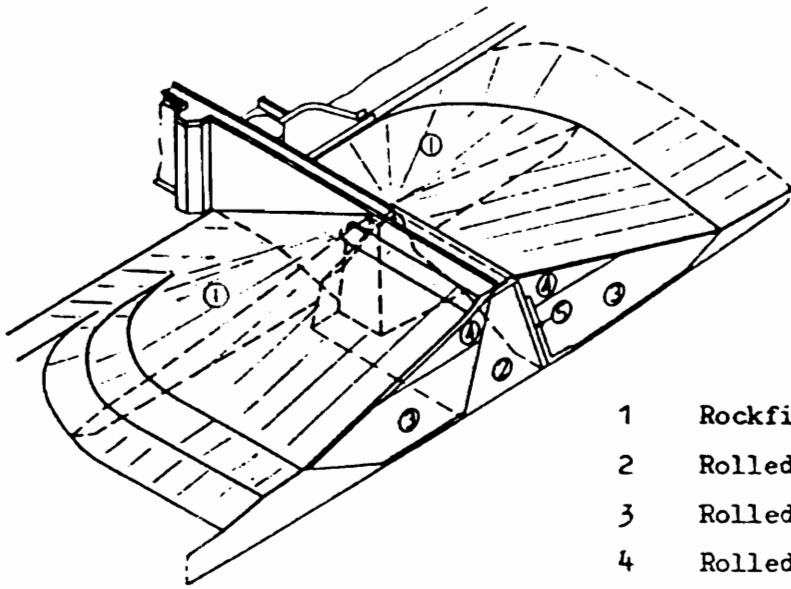
Vaughan and Kennard (1972) reported the results of earth pressure measurements at the Cow Green Dam in northern England. The Cow Green Dam was constructed on the Tees River and consists of a gravity concrete

dam across one side of the valley and an earth embankment dam across the other side. The interface between the concrete dam and the core of the earth embankment was about twenty five meters high. The authors were interested in the performance of the soil-concrete interface with respect to: 1) hydraulic separation at the interface, and 2) hydraulic fracturing within the core material next to the concrete dam.

Earth pressure cells and piezometers were installed at five points on the concrete structure to monitor the soil and pore water pressures. The interface and the locations of the pressure cells are shown in Figure 2.5. Four of the earth pressure cells were installed on the end of the concrete dam and one was installed on the lower part of the upstream face. Piezometers were installed adjacent to each of the earth pressure cells.

The core of the dam is constructed of rolled boulder clay that was placed in 150 mm thick layers. The average as-compacted water content and unit weight of the clay was 14.7% and 22.1 kN/m³, respectively, and the average undrained shear strength was 74 kN/m². A higher water content was used for the core material placed against the concrete dam.

The earth pressure cells were double-sided vibrating wire instruments. Each cell was mounted in synthetic rubber on a cast iron backing piece. This arrangement allowed two pressure readings to be obtained at each location. The piezometers were high air entry ceramic disks mounted in PVC and were connected to mercury manometers with nylon tubing.



- 1 Rockfill
- 2 Rolled Boulder Clay Core
- 3 Rolled Gravel Fill
- 4 Rolled Boulder Clay Fill
- 5 Filters

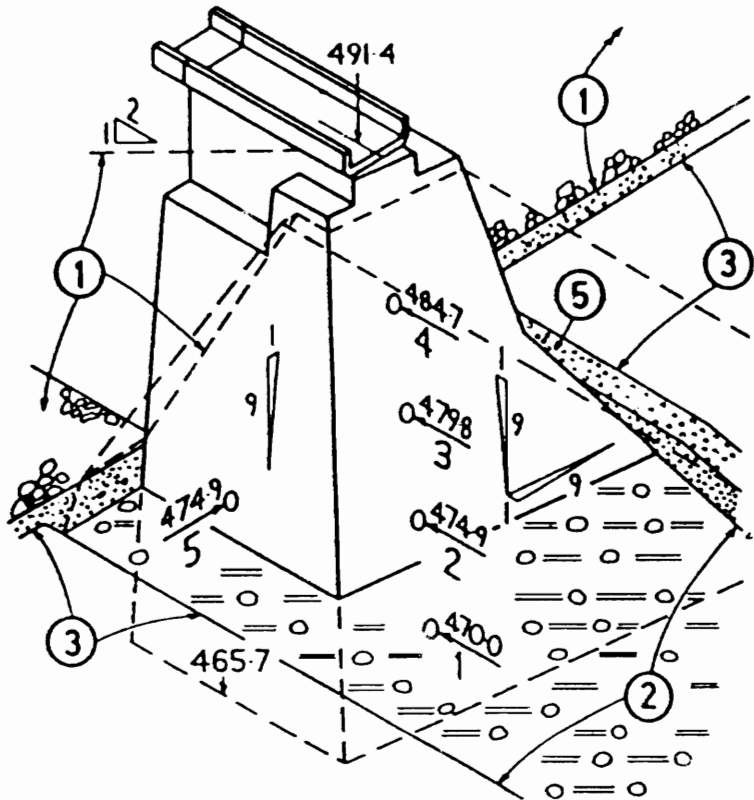


Figure 2.5) Soil-Concrete Interface Detail and Instrumentation Layout, Cow Green Dam (Vaughan and Kennard, 1972).

Figure 2.6 shows the earth pressure and piezometer data. The depth below the top of the fill, for each instrument group, is shown in the upper part of the figure. Two sets of earth pressure data are shown for each location: one marked P_{CA} , representing the pressure reading for the face contacting the soil, and the other marked P_{CB} , representing the face contacting the synthetic rubber. For all cases, except that of cell number 4, the pressure reading on the soil side exceeds the pressure reading on the side contacting the synthetic rubber. The pore water pressure and the earth pressure increase in direct response to the increasing height of the fill.

The data from the four pressure cells on the end of the concrete dam indicate a total stress lateral earth pressure coefficient of 0.60 to 0.72 during construction and 0.67 to 0.72 at the end of construction. Cell number 5, located on the upstream face of the concrete dam, indicated a total stress lateral earth pressure coefficient less than at the other locations. During construction the coefficient was between 0.32 and 0.50, and at the end of construction it was 0.32.

Knowledge of the pore pressure enables the calculation of the earth pressure coefficient in terms of effective stress. Table 2.2 summarizes the pressure readings and the earth pressure coefficients at the end of construction and fourteen months later. At the end of construction the effective stress lateral earth pressure coefficient was between 0.28 and 0.43 on the end of the concrete dam. Fourteen months later the coefficient was essentially unchanged for cell numbers 1 thru 3. The effective stress lateral earth pressure coefficient for cell number 4

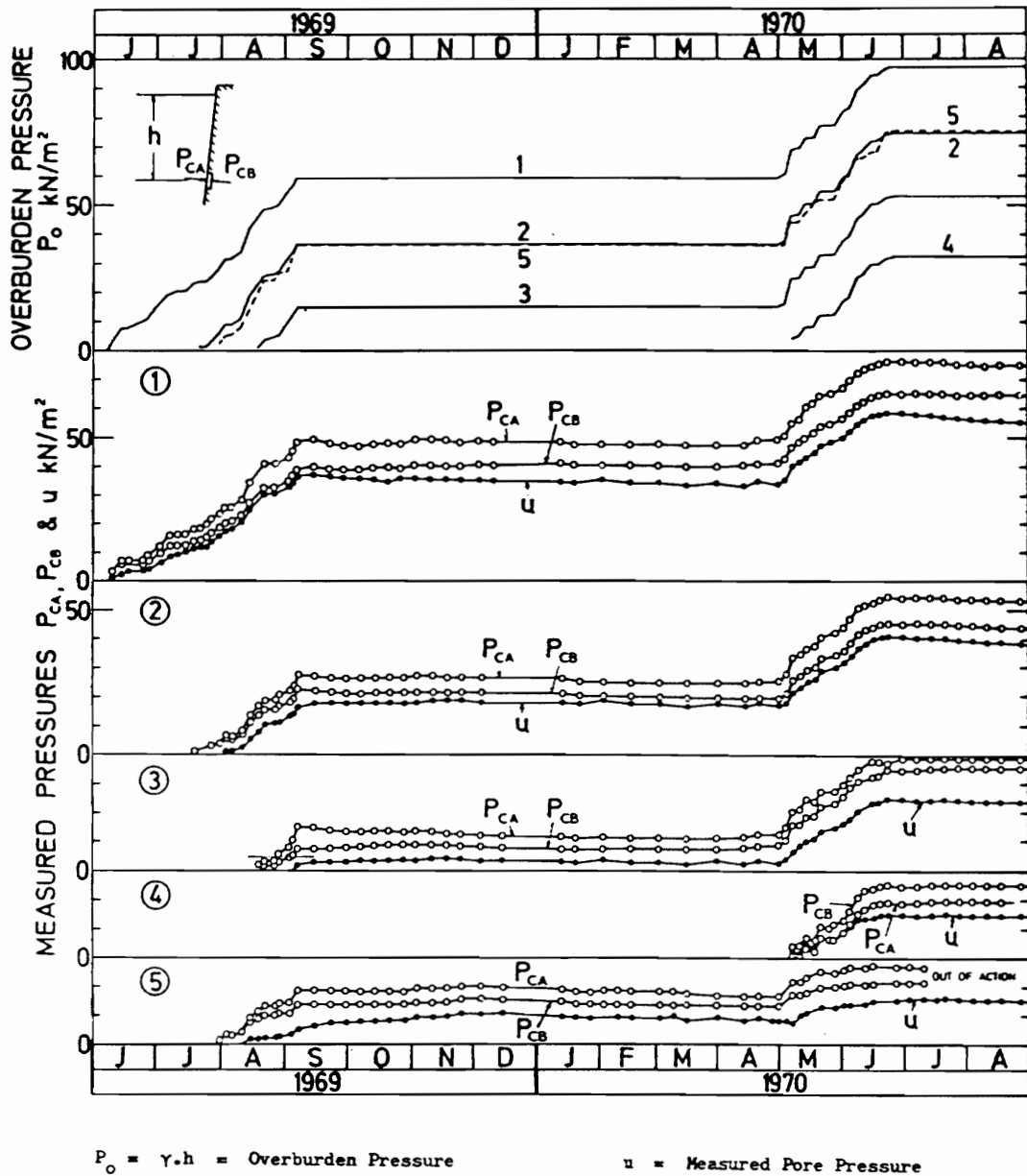


Figure 2.6) Pressures Measured During and After Construction, Cow Green Dam (Vaughan and Kennard, 1972).

Table 2.2) Summary of Pressure Readings for Cow Green Dam (data from Vaughan and Kennard 1972).

Cell No.	June, 1970					August, 1971				
	Pressures (kN/m ²)			Pressure Ratios		Pressures (kN/m ²)		Pressure Ratios		
	P ₀	P _C	u	$\frac{P_C}{P_0}$	$\frac{P'_C}{P'_0}$	P _C	u	$\frac{P_C}{P_0}$	$\frac{P'_C}{P'_0}$	
1	470	364	276	0.72	0.32	301	220	0.64	0.32	
2	364	266	198	0.67	0.28	213	155	0.59	0.28	
3	259	189	119	0.67	0.43	172	104	0.66	0.44	
4	159	93	71	0.68	0.43	96	66	0.60	0.32	
5	369	133	78	0.32	0.14	---	84	----	----	

Notes : P₀ = Total vertical pressure (γz)
P_C = Average lateral pressure (P_{CA} + P_{CB})/2
u = Pore pressure
P₀' = Effective vertical pressure (P₀ - u)
P_C' = Effective lateral pressure (P_C - u)

decreased from the after construction value of 0.43 to 0.32 over the fourteen month period.

2.2.4 Coyle and Bartoskewitz (1977)

A five-year study of earth pressures on retaining walls was conducted at Texas A & M University, beginning in 1970. The study included an evaluation of several types of earth pressure cells and the instrumentation of two retaining walls. The objective of the study was to develop new retaining wall design criteria based on the lateral earth pressure measurements. Coyle and Bartoskewitz (1977) presented the principal findings and conclusions of the study. Earlier reports and papers, which contain preliminary findings and describe the study in more detail, include: Coyle and Bartoskewitz (1976), Wright, et al. (1975), Coyle, et al. (1974), Prescott, et al. (1973), Coyle, et al. (1972), and Corbett, et al. (1971). Information from these earlier reports is included in this section.

The study began with a review of instruments available to measure earth pressures on retaining structures. Corbett, et al. (1971) discuss the operating principles of 7 basic types of pressure cells: 1) the Goldbeck cell, 2) the Carlson cell, 3) the Waterways Experiment Station cell, 4) the Geonor cell, 5) the Gloetzl cell, 6) the Terra Tec cell, and 7) the LVDT cell. Specific information relating to physical dimensions, operating principle, cost, availability, and expected performance was compiled and reviewed for nine commercially available pressure cells. Based on this information and previous performance

records, four earth pressure cells were chosen for further evaluation: 1) the Gloetzl cell, 2) the Terra Tec cell, 3) the Geonor cell, and 4) the Carlson cell.

Two pressure cells of each type were installed on an 18-foot-high concrete retaining wall to evaluate their field performance. Based on this evaluation, the Geonor and Terra Tec cells were chosen for use during the remainder of the study.

Two retaining walls, associated with Texas Highway Department construction in Houston, were selected for instrumentation: 1) a cantilever retaining wall, and 2) a precast panel retaining wall. These walls are discussed in the following sections.

2.2.4.1 Cantilever Retaining Wall, Highway US 59, Houston, Texas.

Seven cantilever retaining walls were constructed near the intersection of highway US 59 and Interstate 45 in Houston, Texas. A section of one of the walls, designated test wall G, was selected for instrumentation. The cantilever retaining wall and its base are supported on steel H piles. Four Terra Tec and two Geonor earth pressure cells were installed on the wall. The cells were mounted with their faces flush with the face of the wall, and thermocouples were installed next to each pressure cell. Figure 2.7 shows a cross section and an elevation of the wall and the locations of the pressure cells.

The backfill material, a tan uniform fine sand with $D_{10} = 0.07$ mm, $D_{60} = 0.23$ mm, and $C_u = 3.3$, classifies as SP-SM using the Unified Classification System. The fill was deposited by scrapers and spread

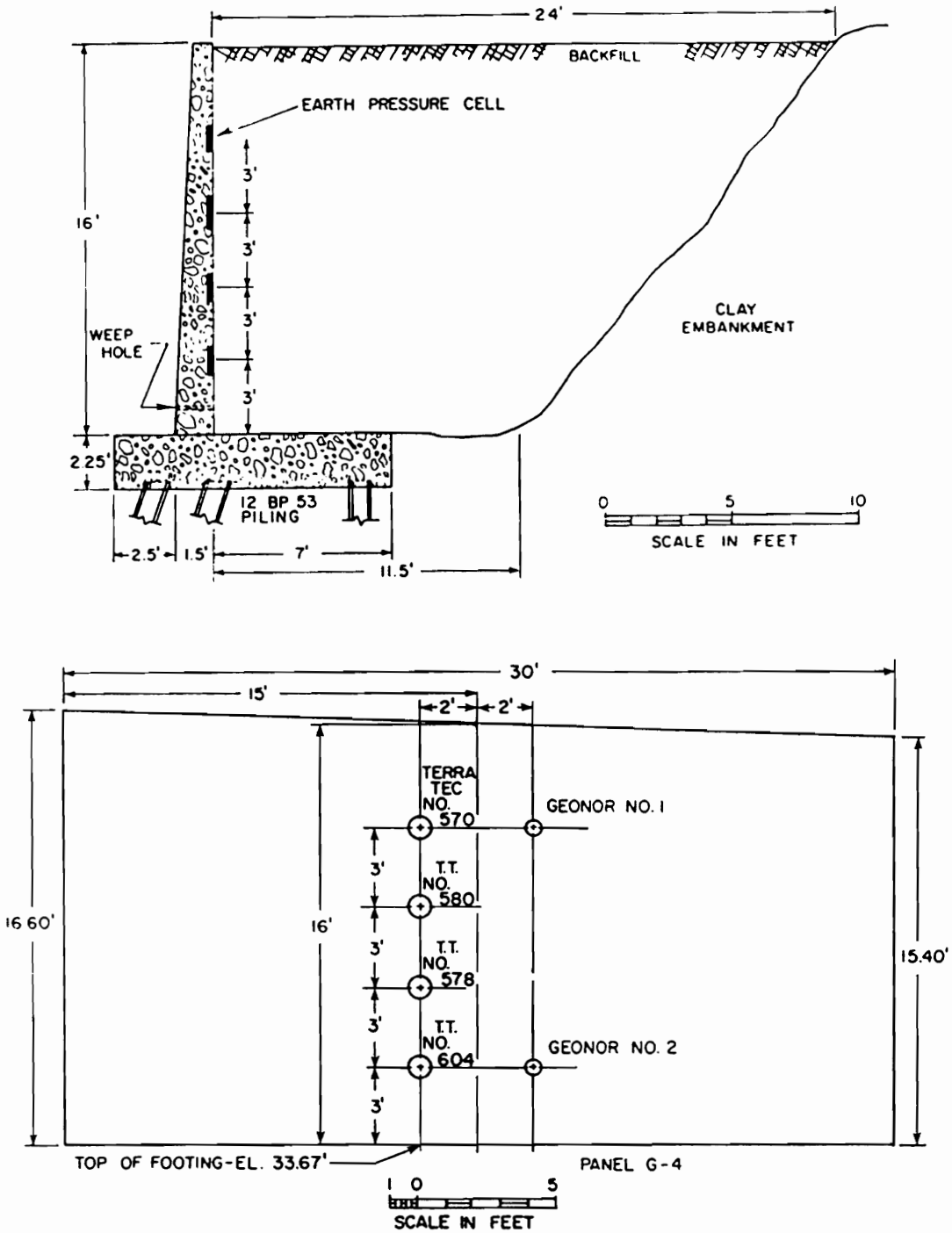


Figure 2.7) Cross Section and Elevation of Test Wall G, Highway US-59, Houston, Texas (Wright, et al., 1975).

into 8 inch lifts by a bulldozer. Each lift was compacted by about 3 passes of the bulldozer. The backfill total unit weight varied from 78 to 116 lbs/ft³ near the wall and from 85 to 122 lbs/ft³ at the center of the fill. Moisture contents for both locations were between 15% and 23%.

Pressure, temperature, and displacement data were collected during construction and for about 3 years after construction. Temperature readings were used to correct the pressure readings, based on an earlier investigation of the temperature effects on the pressure readings. The corrected earth pressures recorded during the construction period are shown in Figure 2.8. The total stress lateral earth pressure coefficient ranged from 0.60 to 0.91 at the end of construction.

The long-term pressure record, shown in Figure 2.9, indicates a cyclic seasonal pattern, particularly for earth pressure cell numbers 578 and 604. Pressures tended to be higher during the summer months and lower during the winter months. The seasonal fluctuation is about 40 percent of the mean pressure.

The measured displacements are shown in Figure 2.10. According to Wright, et al. (1975) and Coyle and Bartoskewitz (1977), the displacement data are only useful to characterize the wall movements, due to potential inaccuracies in the displacement measuring system. The wall movements were primarily translational while fill was being placed against the lower portion of the wall, days 1 and 2. Between days 2 and 6, while fill was being placed against the upper portion of the wall, the movements were primarily rotational. The measurements indicate that

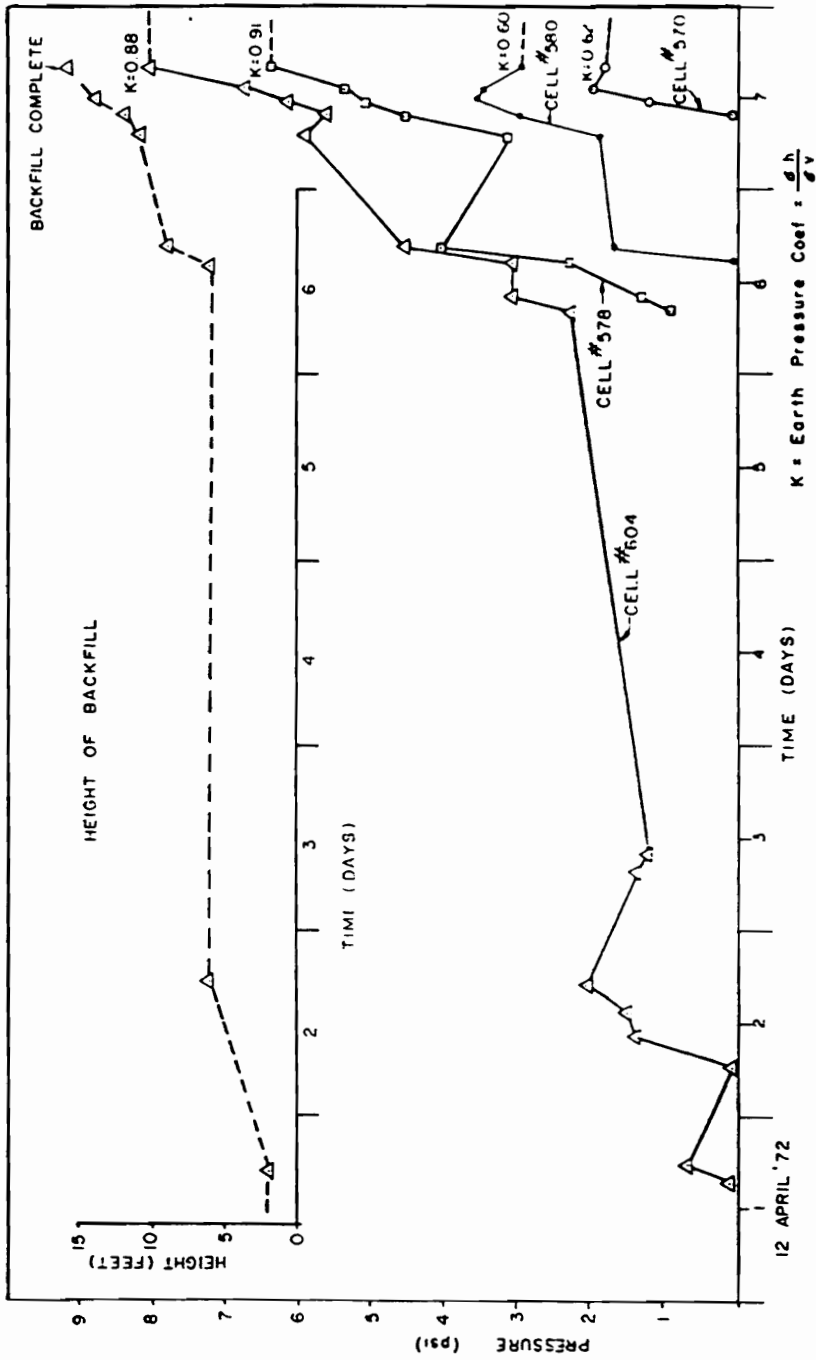


Figure 2.8) Earth Pressures Measured During Construction, Test Wall G, Highway US 59, Houston, Texas (Wright, et al., 1975).

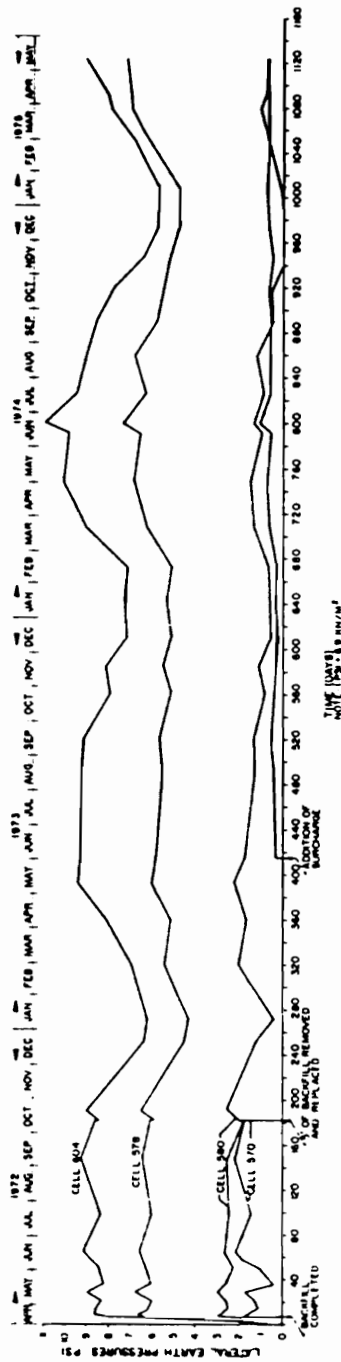


Figure 2.9) Long Term Pressures Measured on Test Wall G, Highway US 59, Houston, Texas (Wright, et al., 1975).

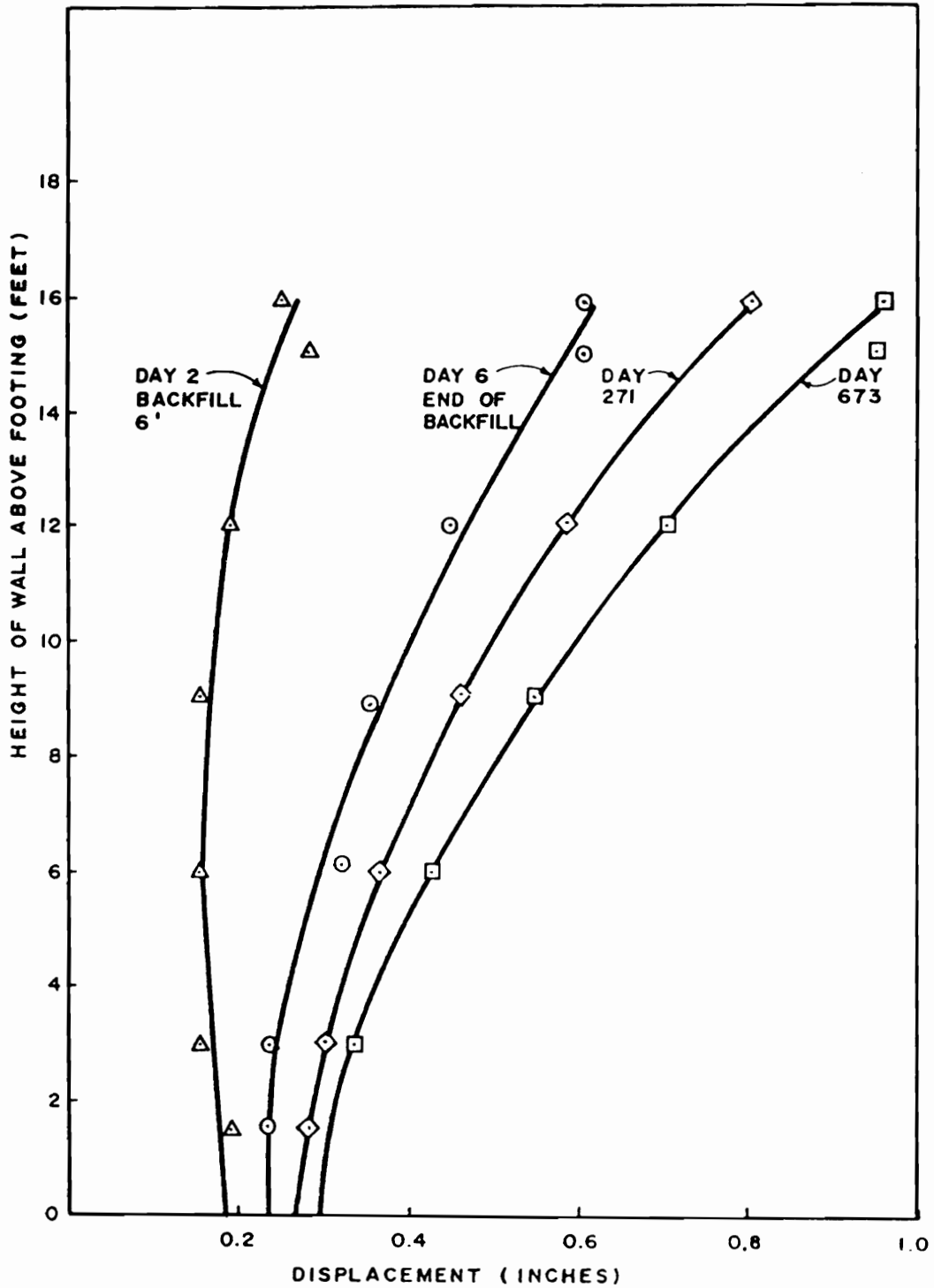


Figure 2.10) Measured Wall Displacements, Test Wall G, Highway US-59, Houston, Texas (Wright, et al., 1975).

the wall continued to yield slowly (about 5 mm/year, measured at the top of the wall) during the 22 month observation period.

2.2.4.2 Precast Panel Retaining Wall, Highway US 290, Houston, Texas

Four retaining walls were constructed at the intersection of highway US 290 and Dacoma Street in northwest Houston, Texas. A section of one of the walls was selected to be instrumented.

The retaining wall was constructed of precast concrete panels supported by T-shaped concrete pilasters as shown in Figure 2.11. Each concrete pilaster was constructed on a 3 ft. 2 in. square by 16 in. thick footing founded on a 3 ft. diameter by 20 ft. deep drilled shaft. The instrumented panel was 9 ft. 10 in. high by 10 ft. 8 in. long and was supported vertically on neoprene pads.

Lateral earth pressures were measured with nine Terra Tec earth pressure cells. The total thrust on the panel was measured with four force transducers installed between the concrete wall panel and the supporting pilasters. Thermocouples were installed at all pressure cell and force transducer locations. Wood timbers were placed between the two supporting pilasters to prevent the fill placed in front of the wall from influencing the force measurements. The instrument locations, structural elements and backfill conditions are shown in Figure 2.12.

The backfill material, a uniform fine sand with $D_{10} = 0.08$ mm, $D_{60} = 0.26$ mm, and $C_u = 3.3$, classifies as SP-SM using the Unified Classification System. Based on direct shear tests, the effective friction angle for the sand was estimated to be 32° .

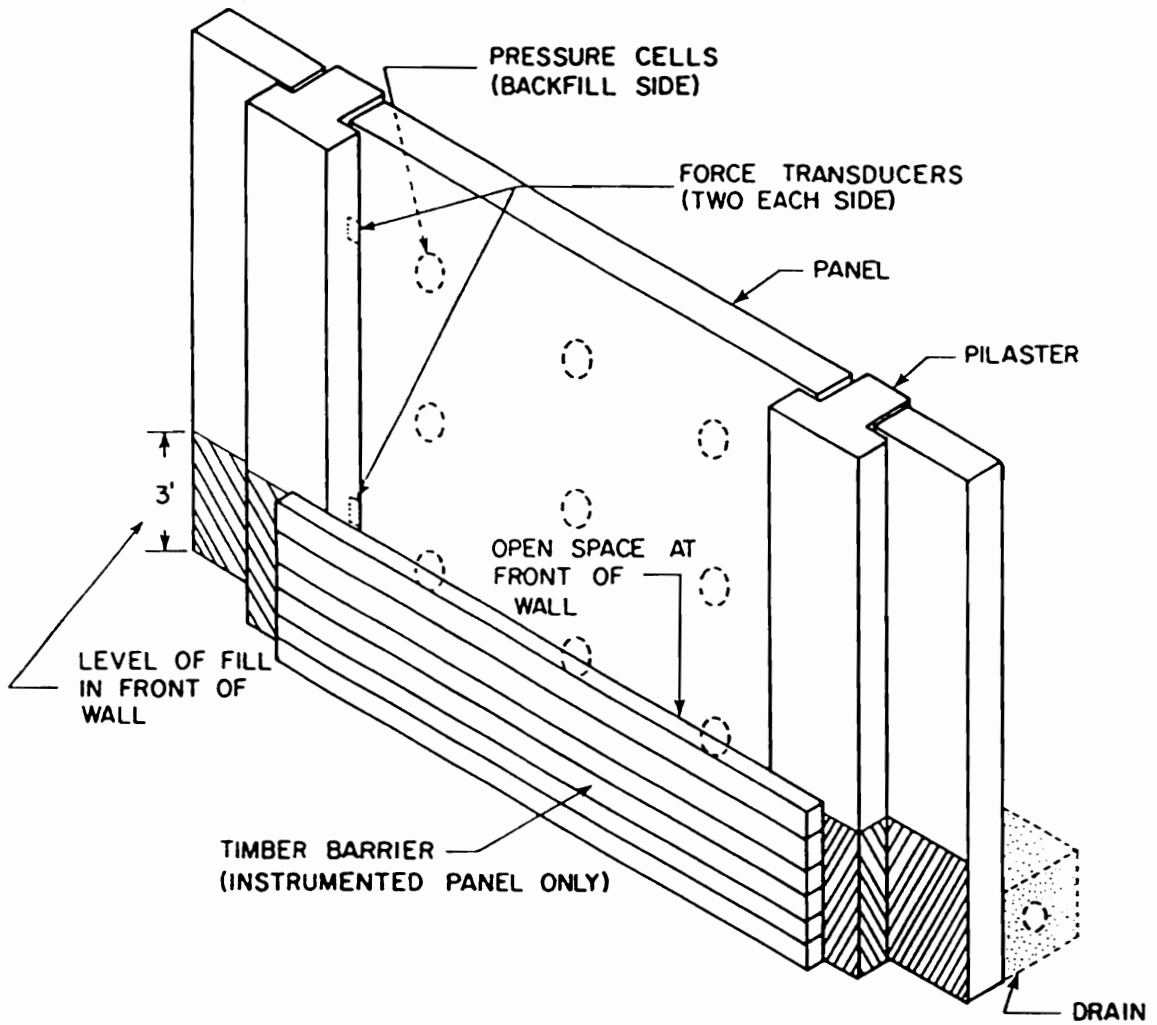


Figure 2.11) Precast Panel Retaining Wall, Highway Us 290, Houston, Texas (Wright, et al., 1975).

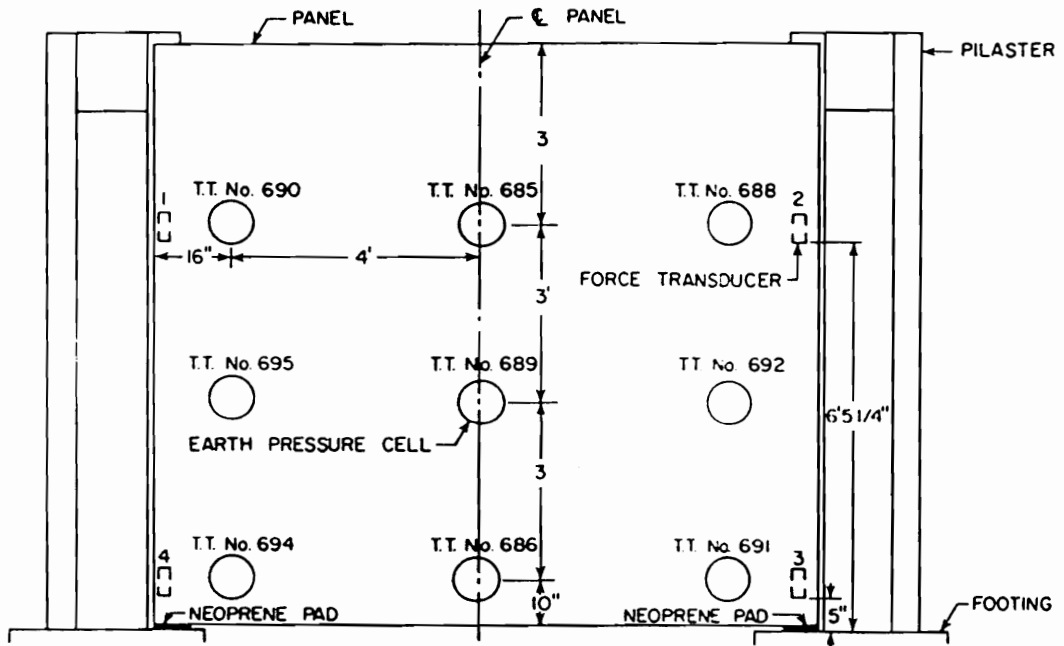
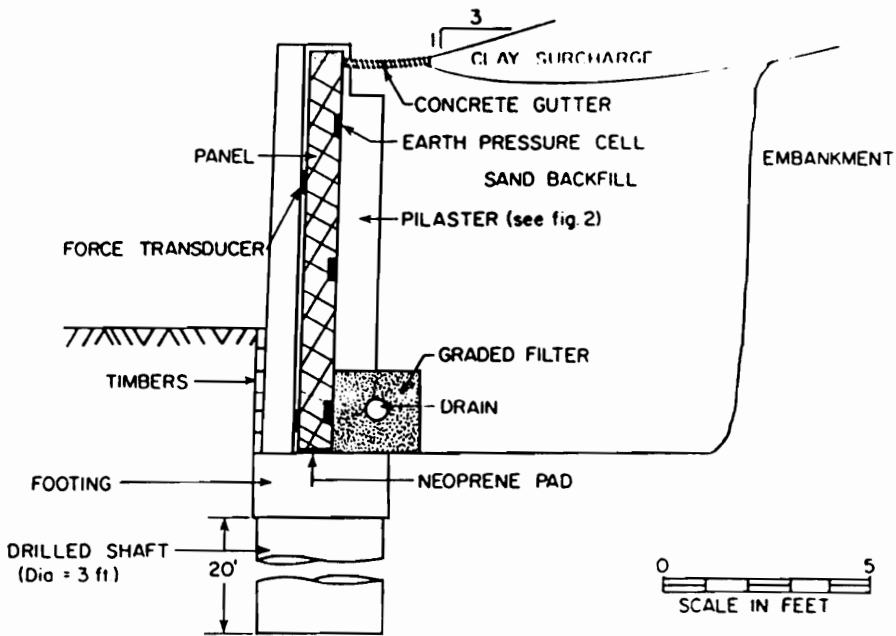
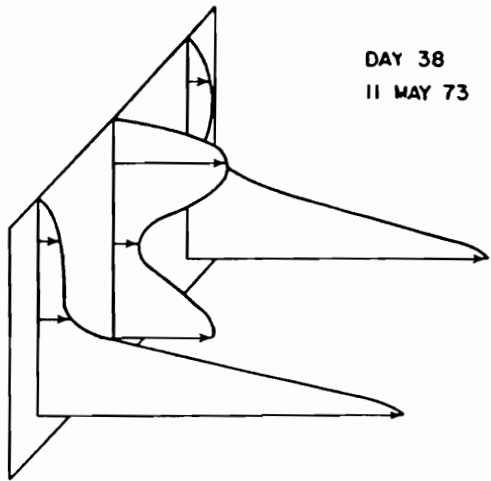


Figure 2.12) Cross Section and Elevation of Panel Retaining Wall, Highway US 290, Houston, Texas (Wright, et al., 1975).

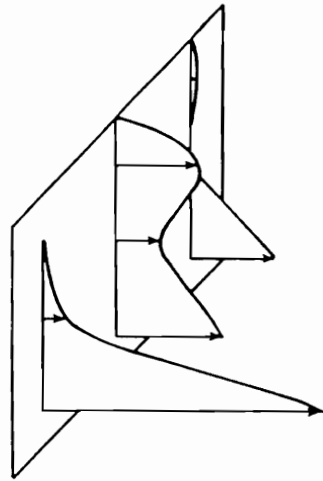
The fill was compacted in six-inch-thick lifts with vibratory rollers. The moisture content and unit weight were carefully controlled during construction. The average compacted dry unit weight of the sand was 95 lbs/ft³, and the average moisture content was 10 percent. The clay surcharge, shown in Figure 2.12, was compacted to an average dry unit weight of 106 lbs/ft³ at an average moisture content of 15 percent.

The measured earth pressures, at four different times during the study, are shown in Figure 2.13. The measurements indicate a very complex distribution of earth pressure on the wall panel. The average earth pressures at each instrument level are shown in Figure 2.14. Figure 2.14a represents the period before the clay surcharge was placed and Figure 2.14b represents the period after placement of the clay surcharge. Both cases indicate general agreement between the measured and theoretical values in the upper 6 ft. of the fill. At a depth of 9 feet, the measured pressures exceeded the theoretical values for all of the times represented.

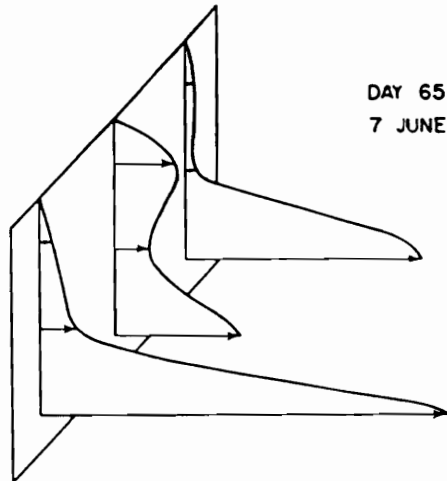
The horizontal forces, measured by the four load cells that support the wall laterally, are shown in Figure 2.15. The measured forces increased during construction and became relatively constant, on the average, after construction. The two-year record does not indicate any long-term trends. However, it does reveal a slight seasonal fluctuation with higher pressures during the summer and fall and lower pressure during the winter and spring. This seasonal pattern was also noticed on the cantilever wall reviewed in the previous section.



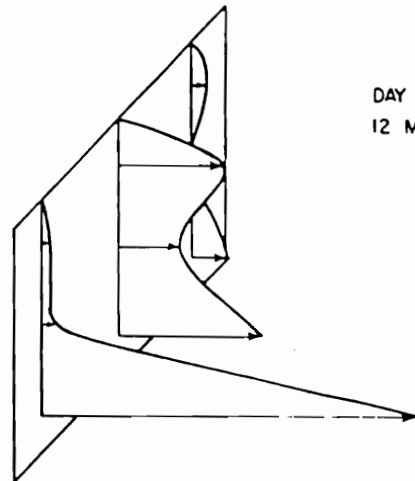
DAY 38
11 MAY 73



DAY 316
13 FEB 74

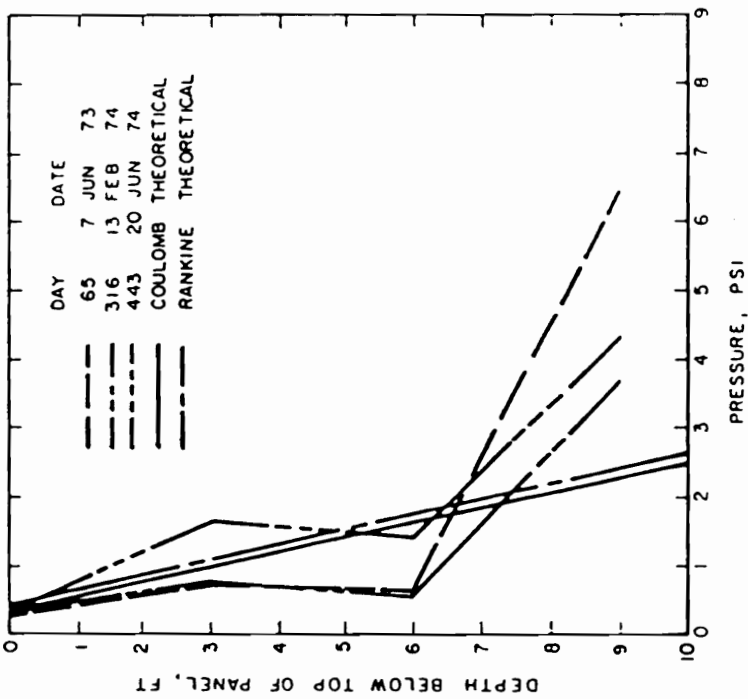


DAY 65
7 JUNE 73

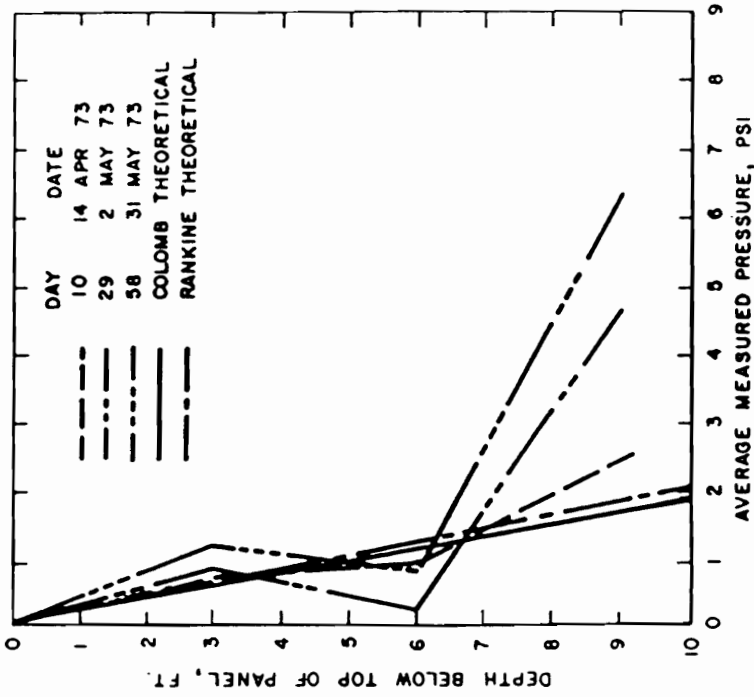


DAY 769
12 MAY 75

Figure 2.13) Typical Measured Pressure Distributions, Panel Retaining Wall, Highway US 290, Houston, Texas (Wright, et al., 1975).



a) without clay surcharge



b) with clay surcharge

Figure 2.14) Average Measured Pressures, Panel Retaining Wall, Highway US 290, Houston, Texas (Coyle and Bartoskewitz, 1976).

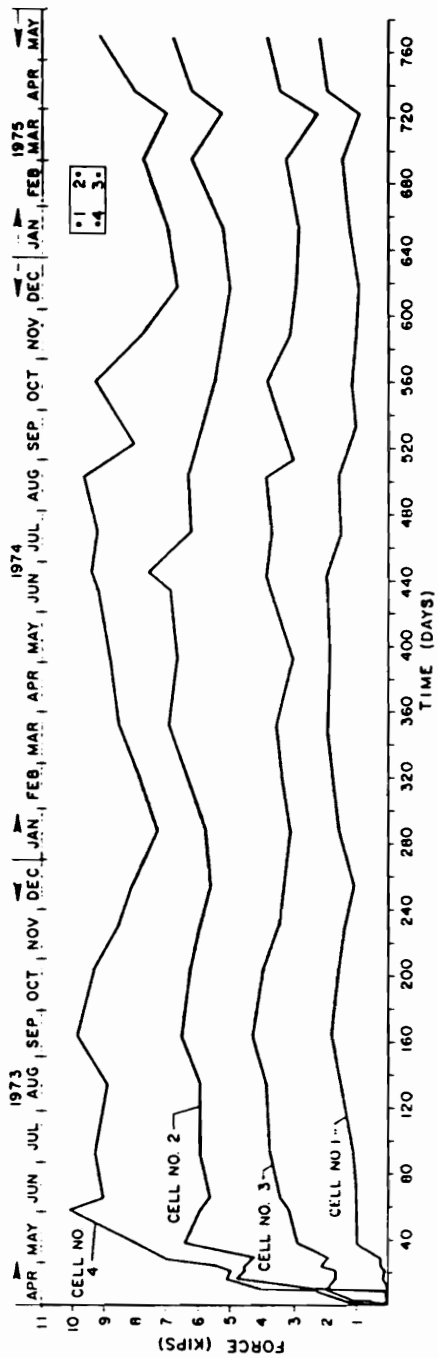


Figure 2.15) Measured Horizontal Reaction Forces, Panel Retaining Wall, Highway US 290, Houston, Texas (Wright, et al., 1975).

Displacement measurements are shown in Figure 2.16. The movements were greatest during construction and continued, at a decreasing rate, during the remainder of the two-year observation period.

2.2.5 Roth, Lee, and Crandall (1979)

Roth, et al. (1979) reported on the measurement of earth pressures on the walls of a deep basement of a high-rise office building in Los Angeles, California. The primary objective was to collect earth pressure data during seismic events. To do this, nine Carlson earth pressure cells were installed on the walls of the basement during construction and connected to an automatic recorder that would record the pressure-time data when triggered by a strong-motion earthquake. The earth pressures during construction, for six of the nine pressure cells, were reported by Roth, et al. (1979).

The six Carlson cells were installed at two locations about 80 meters apart. At section 1 the excavation was 34.4 meters deep, with a side slope of 3/5 horizontal to 1 vertical. At section 2 the excavation was 31.3 meters deep, with a side slope of 2/3 horizontal to 1 vertical. The Carlson earth pressure cells were mounted with their pressure sensing faces flush with the wall surface. The backfill conditions were fairly complex and, starting at the wall, consisted of the following layers: 1) 0.5 cm of corrugated cardboard filled with dry bentonite, 2) 1 cm of soft fiber-board, 3) 90 cm of pea gravel, and 4) compacted silty sand.

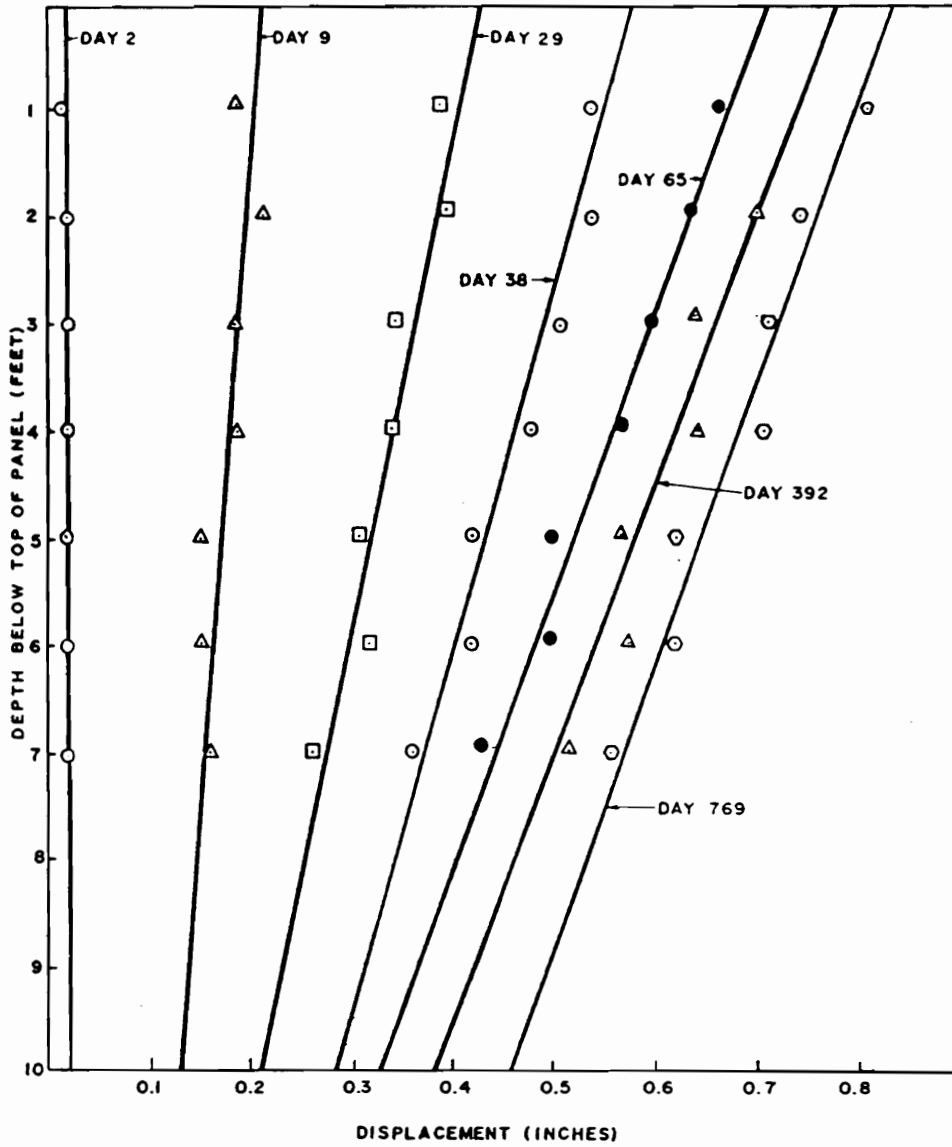


Figure 2.16) Measured Wall Displacements, Panel Retaining Wall, Highway US 290, Houston, Texas (Wright, et al., 1975).

The pea gravel was very uniform, with an average diameter of about 7 mm. The silty sand was well graded, with $D_{60} = 0.4$ mm, $D_{10} = 0.003$ mm, and $C_u = 133$. The friction angle for the silty sand was reported as about 30° .

The silty sand backfill was compacted in 25 cm thick layers, by a vibratory sheepsfoot roller, to about 90 percent of the Modified Proctor maximum density at a water content slightly wet of the optimum. The pea gravel was compacted with a vibratory tamper.

The relationships between the measured lateral pressures and the height of fill above the pressure cells are shown in Figure 2.17 for two pressure cells at section 1, and in Figure 2.18 for two pressure cells at section 2. With the exception of a few data points, the correlation between fill height and lateral pressure is good. The data in Figures 2.17 and 2.18 can be used to calculate the lateral earth pressure coefficient. Based on a backfill unit weight of 2.1 t/m^2 , Roth, et al. calculated earth pressure coefficients between 0.18 and 0.24 for the linear relationships shown in Figures 2.17 and 2.18.

For a stiff retaining structure and a compacted backfill, an earth pressure coefficient of $K_0 = 1 - \sin \phi'$ or higher would be expected. The 30° friction angle of the silty sand corresponds to $K_0 = 0.5$. The measured values, considerably less than 0.5, may be influenced by arching in the relatively narrow backfill zone.

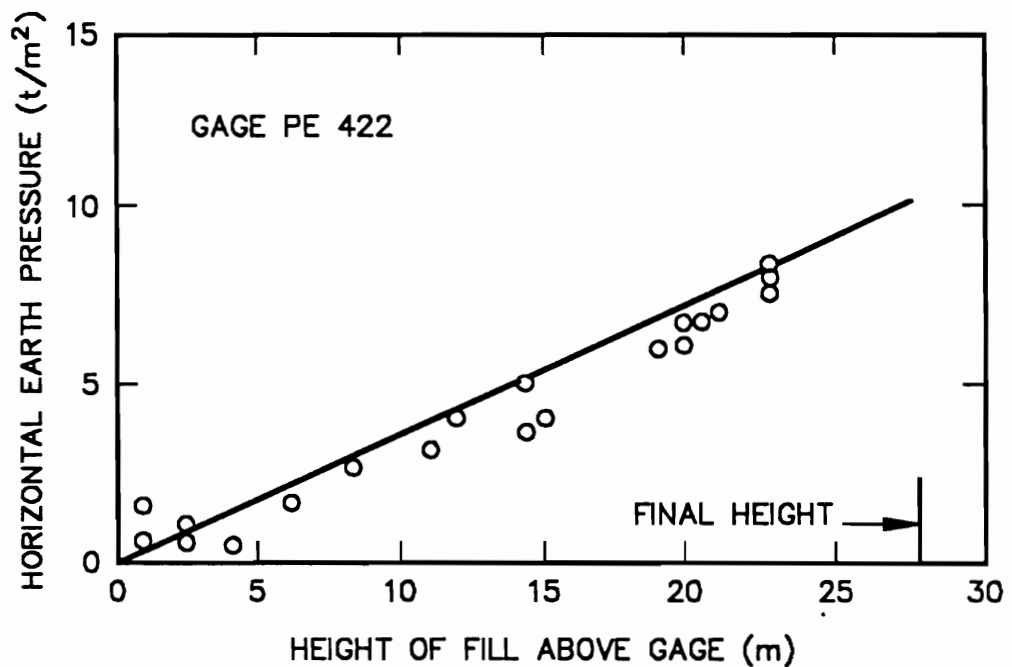
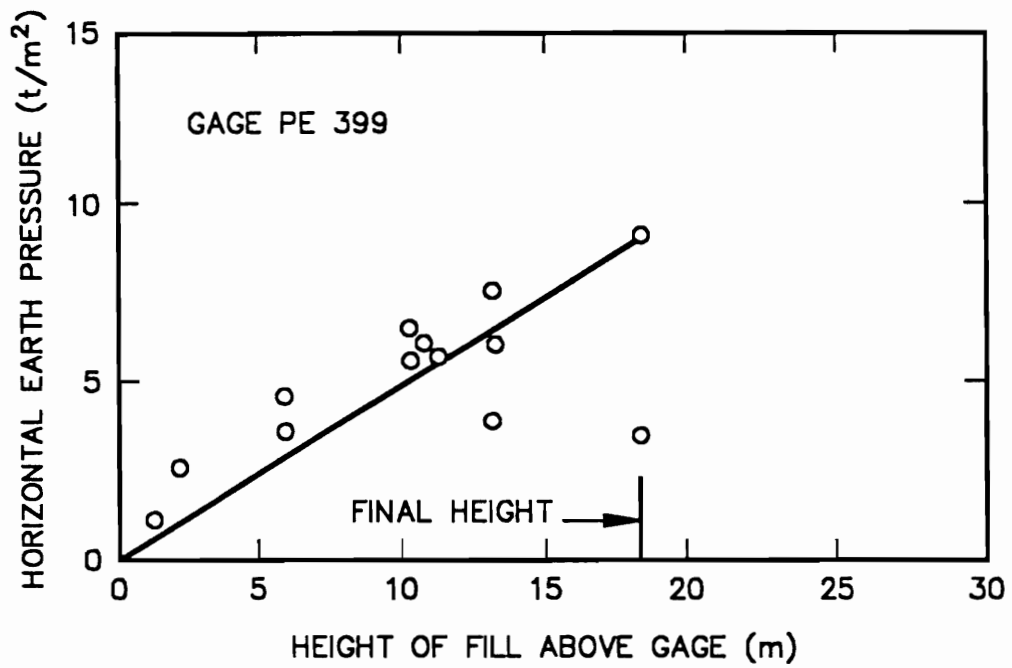


Figure 2.17) Measured Horizontal Earth Pressures at Section 1 (Roth, et al., 1979).

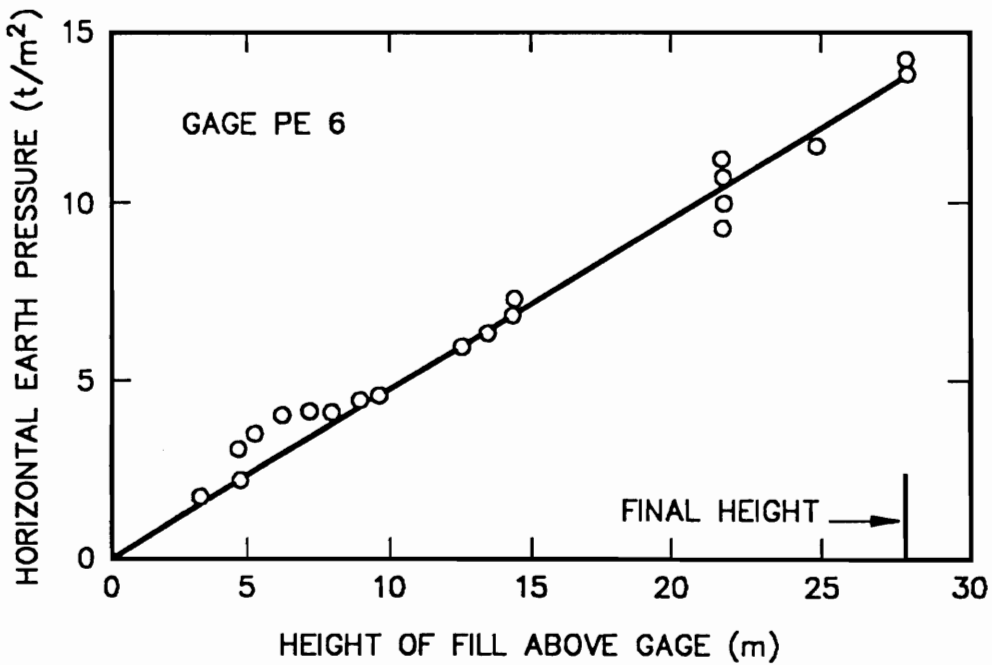
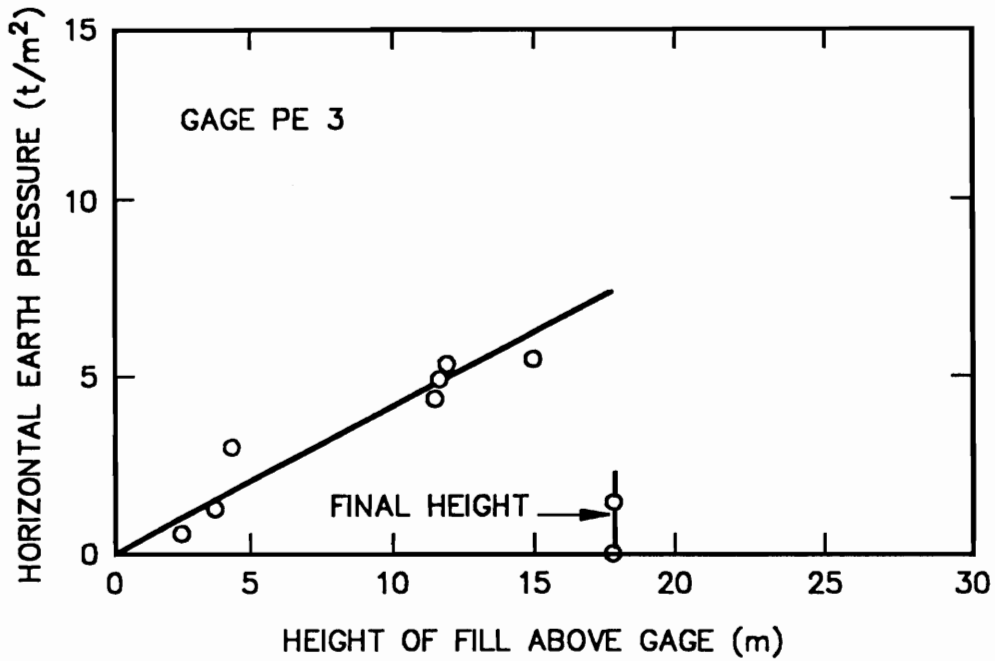


Figure 2.18) Measured Horizontal Earth Pressures at Section 2 (Roth, et al., 1979).

2.2.6 Bruner, Coyle, and Bartoskewitz (1983)

Bruner, et al. (1983) instrumented a section of a retaining wall constructed as part of a Texas State Department of Highways and Public Transportation project. The wall was located near the intersection of State Highway 288 and MacGregor Avenue in Houston, Texas.

The retaining wall, of conventional cantilever design with a base shear key, varied in height along its 382.5 ft. length and was 14 ft. high at the instrumented section. The wall was instrumented with fourteen Terra Tec earth pressure cells and six thermocouples. Lateral wall movements were recorded by measuring the movements of six reference points on the front of the wall. Figure 2.19a shows the locations of the earth pressure cells. The locations of the thermocouples and the points used to measure wall displacements are shown in Figure 2.19b.

Two backfill materials were used: a uniform fine silty sand (SP-SM) and a high plasticity clay (CH). The zoning of the backfill is shown in Figure 2.19b. The silty sand was compacted to an average dry unit weight of 113 lbs/ft³ at an average moisture content of 12%. For the compacted clay, tests indicated dry densities from 98 to 109 lbs/ft³ and moisture contents from 21 to 27 percent. The undrained shear strength of the compacted clay ranged from about 1900 lbs/ft² to about 3000 lbs/ft², based on direct shear tests. The clay had a plasticity index of about 47 and a liquid limit of about 66.

The measured earth pressures on the back of the wall, corrected for temperature effects, are shown in Figure 2.20 for a four month period after construction. The horizontal bars represent the range of

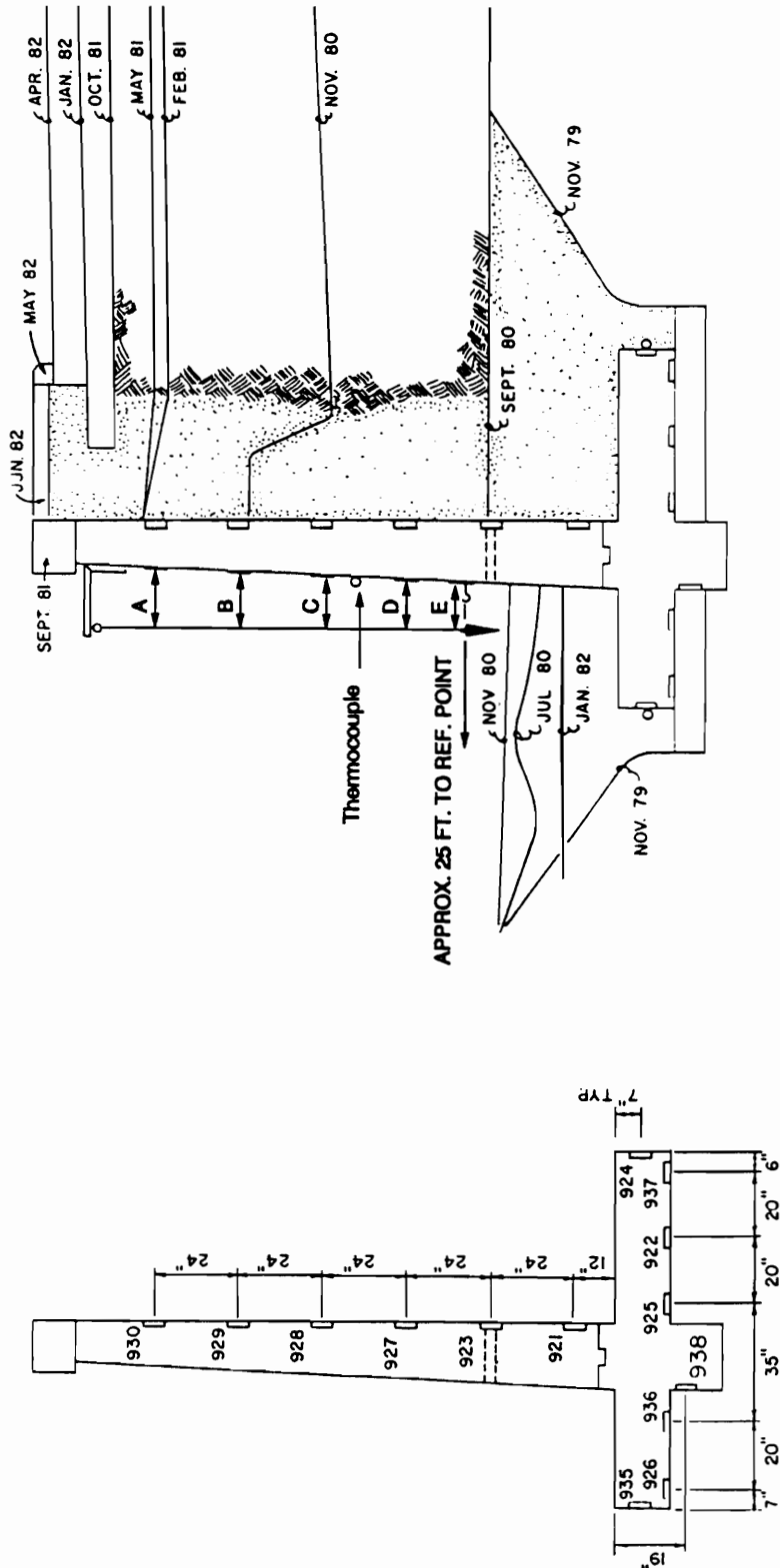


Figure 2.19) Wall Dimensions, Instrument Locations, Backfill Zoning, and Construction Sequence, Cantilever Retaining Wall, State Highway 288, Houston, Texas (Bruner, et al., 1983).

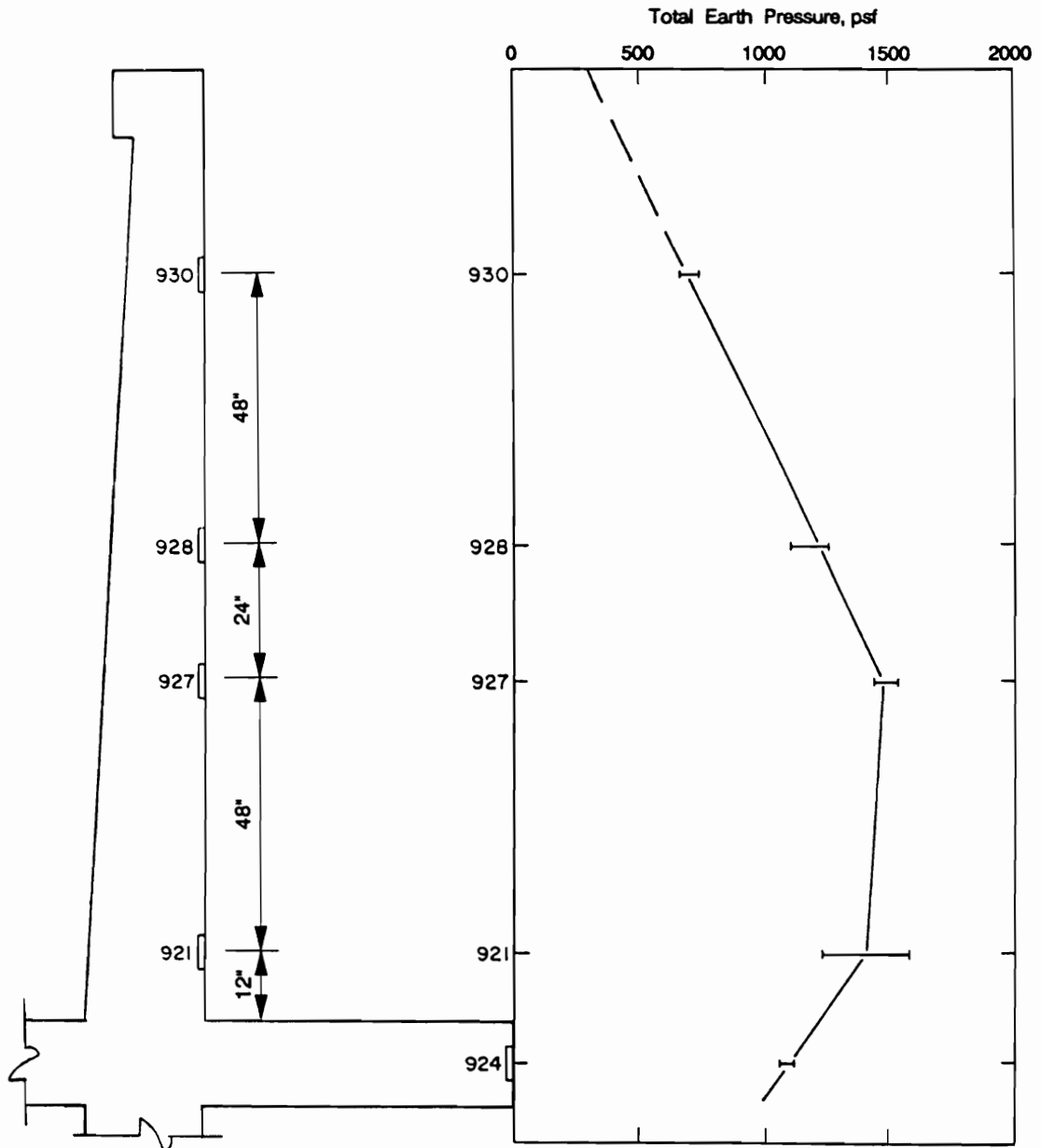


Figure 2.20) Measured Earth Pressures, Cantilever Retaining Wall, State Highway 288, Houston, Texas (Bruner, et al., 1983).

pressures observed during this period. Information for cells number 929 and 923 are not included because these cells became inoperative before measurements began. As interpreted by the authors, the data suggest a 290 lbs/ft² lateral pressure at the surface and a linear increase in pressure of 133 lbs/ft² per foot of depth to a depth of 9 ft. The measured pressures were essentially equal at the 9 ft. and 13 ft. depths, and slightly less at a depth of 14.5 ft.

The measured pressure distribution indicates lateral pressures that correspond to an earth pressure coefficient slightly greater than unity, for the upper portion of the fill. This may indicate a residual lateral stress due to compaction of the backfill. The constant and decreasing pressures with increasing depth, measured in the lower portion of the fill, suggest that arching developed in the narrower portions of the fill, near the bottom of the wall.

Two measuring systems were used to monitor the movements of the wall. The translational movements were determined by measuring the distance between a hook installed on the front face of the wall and a reference point established about 25 ft. in front of the wall. Rotational movements were determined from measurements of the distances between the five reference plates on the front face of the wall and a plumb line, hung from a bracket near the top of the wall. The plumb line and measurement points are shown in Figure 2.19b.

Displacement measurements began on November 6, 1980, after more than one-half of the backfill had been placed. The position of the wall on several dates is shown in Figure 2.21. The wall position indicated for

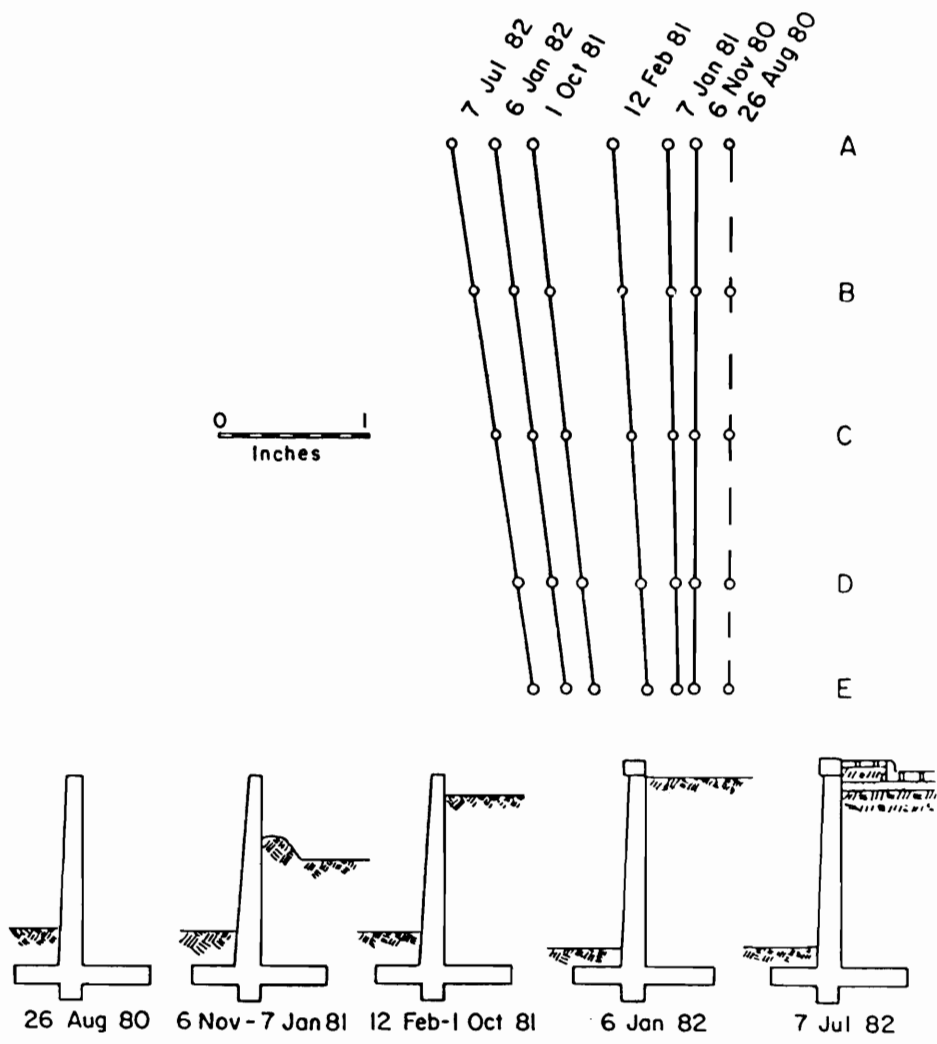


Figure 2.21) Measured Displacements, Cantilever Retaining Wall, State Highway 288, Houston, Texas (Bruner, et al., 1983).

August 26, 1980 was estimated. The accumulated displacement of the top of the wall, between November 6, 1980 and July 7, 1982, is about 1.7 inches, corresponding to $\Delta/H = 0.01$.

The high earth pressures measured against the upper part of the wall and wall movements larger than those generally believed to produce the active condition indicate that backfill compaction can increase wall displacements and earth pressures. Wall yielding during placement and compaction of the upper portion of the backfill may account for the lower stresses measured against the lower portion of the wall.

2.2.7 Vogt, et al. (1986)

Vogt, et al. (1986) reported on the measurement of earth pressures and deformations at Eibach Lock, which is located near Nuremburg, Federal Republic of Germany.

Construction of Eibach Lock began in 1973 and backfilling was completed by September, 1975. During construction, thirty-five earth pressure cells were installed, at nine different depths, to measure the pressures on the lock walls. The earth pressure cells at one section were capable of measuring the shear stresses. Temperature transmitters were installed in the concrete wall to determine the temperature gradient in the wall. Deformations within the backfill were measured by multi-point extensometers. Three extensometers sets were installed vertically and two sets were installed horizontally. The instrumentation arrangement is shown in Figure 2.22.

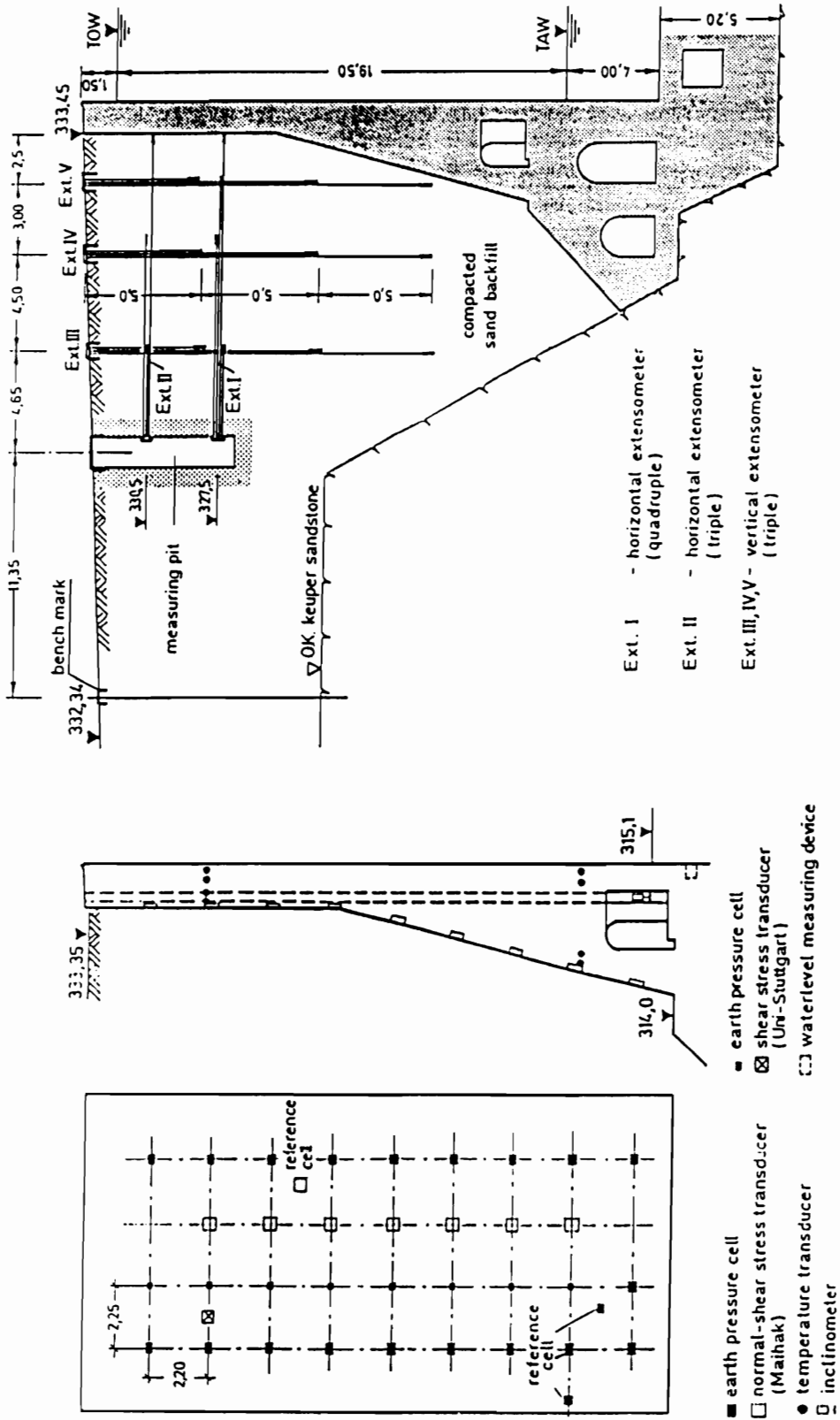


Figure 2.22) Location of Instrumentation, Eibach Lock, Federal Republic of Germany (Vogt, et al., 1986).

Figure 2.23a shows the resultant earth pressure force, calculated from the earth pressure cell data, and the calculated bending moment in the wall at elevation 314.0 m, for a period of about 6 years. The author noted that the individual pressure readings, at a given depth, fluctuated by as much as 10 times their normal value. Fluctuations are common among reported earth pressure measurements and reduce the confidence that can be placed in the measurements. However, the large number of earth pressure cells at the Eibach Lock helps to increase the accuracy of, and the confidence in, the calculated earth pressure resultant forces. The magnitude of the resultant earth pressure force increased over the first year and subsequently followed an annual cycle of increased force during the summer and decreased force during the winter for the remaining 5 years. The average resultant force, on an annual basis, stayed almost constant from 1977 through 1981.

The displacements measured at the top of the wall, shown in Figure 2.23b, are also cyclic. The displacement cycle corresponds with the cycle observed in the earth pressure measurements. The earth pressure is greatest when the wall has moved toward the backfill and least when the wall has moved away from the backfill. Measured temperature gradients within the lock wall indicated that the annual deflection cycle was driven by differential warming and cooling of the lock wall.

The measurement of shear forces at Eibach Lock provided valuable information on the magnitude of the shear force present on full scale earth retaining structures. This aspect of earth pressures is particularly difficult to measure in the field, and few cases have been

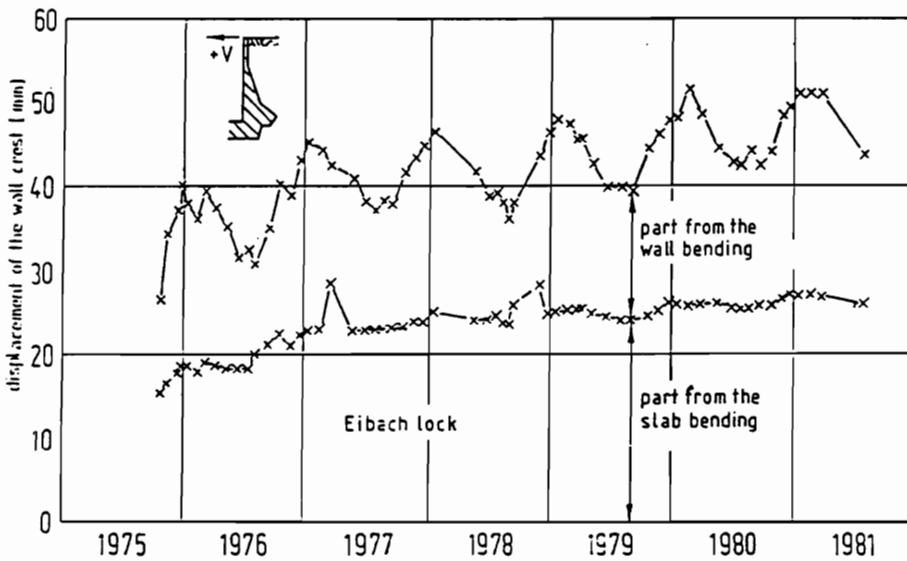
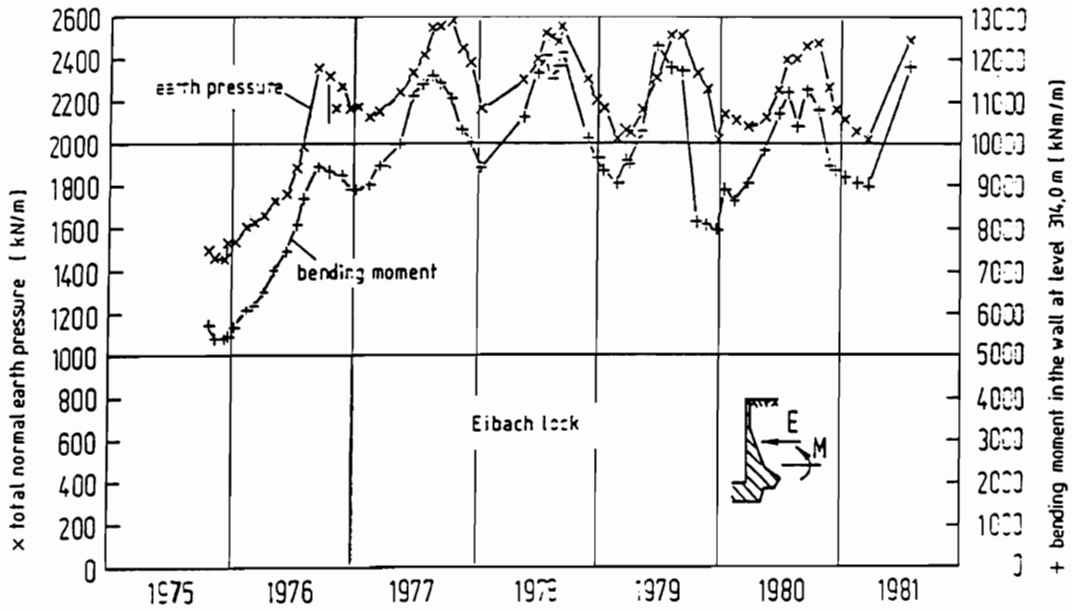


Figure 2.23) Measured Earth Pressures and Displacements and Calculated Moments, Eibach Lock, Federal Republic of Germany (Vogt, et al., 1986).

reported in the literature. The average mobilized wall-friction angle, based on measurements from 8 instruments, is shown in Figure 2.24. The mobilized wall-friction angle ranged from about 21° to almost 41° over the observation period of nearly six years. Perhaps more significant than the actual mobilized shear force is the fact that no decreasing trend was observed over a period of almost six years. This suggests that the vertical shear force on retaining structures persists over a long period, and that it may logically be included in stability calculations as a stabilizing force.

The range of the mobilized wall friction angle measured at the Eibach Lock is in agreement with the value of 27° calculated by Duncan and Clough (1971) using the finite element method to analyze Port Allen Lock. The measurements obtained from an instrumentation program at Port Allen Lock, as reported by Kaufman & Sherman (1964), support the value calculated by Duncan and Clough (1971).

2.3 MODEL WALL STUDIES

About two dozen experimental studies of earth pressures using model walls were reviewed. The model walls ranged in size from 10 cm long by 20 cm high (Frydman and Keissar, 1987) to 6 m long by 10 m high (Matsuo, et al., 1978). The backfill materials included crushed stone, sand and gravel mixtures, and fine grained cohesive and non-cohesive materials.

Table 2.3 contains a summary of these studies. Each entry in the table includes the source of the information, a description of the model

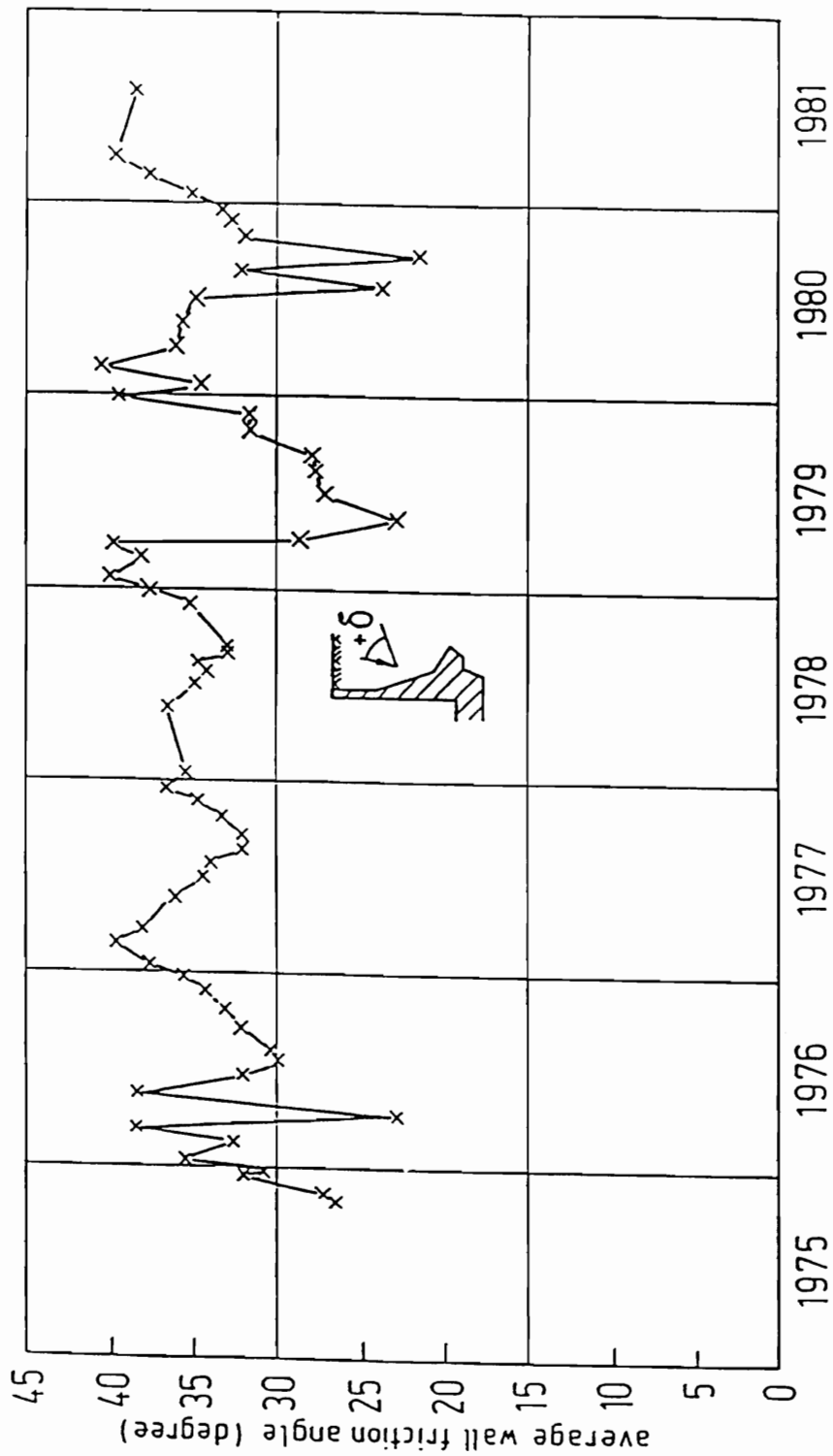


Figure 2.24) Measured Wall Friction Angle, Eibach Lock, Federal Republic of Germany (Vogt, et al., 1986).

Table 2.3) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
Terzaghi, C. 1920	Experiments with coarse and fine beach sand, fine river sand, flint powder, and beans	K = 0.42 for the at-rest condition. K = 0.15 to <0.05 for the fully active condition. For vertical walls, $\Delta/H \approx 0.007$ to reach the fully active condition, where Δ is the wall displacement measured at the mid-height of the wall.
Terzaghi, K. 1934a	14 ft. long x 14 ft. wide x 7 ft. high test bin, instrumented wall on one side, Terzaghi (1932), backfilled with dry Plum Island sand, uniform, medium, angular, $D_{10} = 0.54$ mm, $C_u = 1.7$, $e_{max} = 0.46$, $e_{min} = 0.38$	Without wall movement, K = 0.35 to 0.7 for compacted fill and K \approx 0.4 for loose fill. For compacted fill, outward wall movement of $\Delta/H = 0.001$ reduced K to its minimum value of about 0.1. Similar inward wall movements produced K = 2.0 to 2.5. For loose fill, outward movements of $\Delta/H \geq 0.008$ were required to reduce K to the fully active condition, while inward movements of $\Delta/H = 0.001$ increased K to about 1.0. The wall displacement, Δ , was measured at the mid-height of the wall.
Terzaghi, K. 1934b	Wall and backfill same as Terzaghi (1934a)	Experiments on the effect of saturation of a sand backfill on the pressure exerted on a retaining structure. For sand backfill with the water table at the surface, the pressure on the wall is the hydrostatic water pressure plus the lateral pressure of the soil, taking into account the effect of buoyancy on the pressure due to the soil.
Terzaghi, K. 1934e	Same wall as Terzaghi (1934a), backfilled with modified glacial till, $D_{10} = 0.016$ mm, $C_u \approx 20$	Experiments on the effects of saturation and partial saturation on the pressure exerted by a fine grained backfill on a retaining structure. For both the saturated and partially saturated conditions, the pressure is the water pressure plus the pressure of the soil, taking into account the effect of pore pressure on the pressure due to the soil.

Table 2.3 Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
Spangler, M. G. 1938	6 ft. high reinforced concrete cantilever wall centered on a 30 in. wide x 12 in. deep strip footing, backfilled with pit-run gravelly sand, 40% gravel, 48% sand, 12% fines	Backfill was placed by hand without compaction. Instrumentation consisted of pressure cells and friction ribbons to measure the lateral pressures resulting from small area loads and finite strip loads applied to the surface of the fill. Despite the considerable scatter in the test data, qualitative agreement with the pressure distribution calculated using Boussinesq's theory was noted. Quantitative agreement was improved when the Boussinesq pressures were factored by $K x^{-n}$ where K and n are empirical constants and x is the distance from the load to the wall. For the test data, $K = 1.1$ and $n = .25$ provided reasonable agreement between the calculated and the experimental values.
Jansson, H., Wickert, A., and Rinkert, A. 1948	6 m long x 4 m wide x 2 m high test bin, 6 m x 2 m instrumented wall backfilled with crushed stone, $D = 35$ to 75 mm, $\phi' = 40^\circ$	$K = 0.22$ when the fill was placed in horizontal layers. $K = 0.28$ when the fill was placed in layers dipping 45° toward the wall, near the wall, and in horizontal layers beyond. Measurements indicated $\Delta\sigma_H/\Delta\sigma_V \approx 0.22$ to 0.28 , where $\Delta\sigma_V$ is the applied surcharge and $\Delta\sigma_H$ is the measured change in lateral pressure. About 60 to 70 percent of the $\Delta\sigma_H$ remained after removal of the surcharge. $\Delta/H = 0.0003$, measured at the top of the wall, resulted in a reduction of the measured pressure coefficient to a value close to the theoretical active pressure coefficient, $K_a = 0.217$.
Spangler, M. G. and Mickle, J. L. 1956	10 ft. high x 20 ft. long reinforced concrete cantilever wall centered on a 5 ft. 9 in. wide x 18 in. deep strip footing, backfilled with pit-run gravelly sand, 40% gravel, 48% sand, 12% fines	Backfill was placed by hand without compaction. Instrumentation consisted of pressure cells and friction ribbons to measure the lateral pressures resulting from surcharge loads. In general, the measured pressures agreed with two times the pressure calculated using Boussinesq's theory. For some cases the agreement was poor. Pressures measured after removal of the surcharge indicated residual pressures due to the surcharge loading. The authors concluded that the scatter in the observed pressure values is inherent in the problem of earth pressures on retaining structures.

Table 2.3 (Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
Sowers, G. F., 1957 Robb, A. D., Mullis, C. H., and Glenn, A. H.	Concrete lined test pit, 8 ft. long x 5 ft. wide x 5 ft. deep, backfilled with sand	Two moisture contents were used (about 2% and about 14%) and each was placed with compaction and without compaction. For both moisture contents the residual lateral stresses after compaction were higher than for the uncompacted soil. The after compaction stresses for $w \approx 14\%$ were higher than for $w \approx 2\%$.
Rinkert, A. 1959	Same facility as Jansson, et al. (1948), two backfill materials: a) macadam (crushed stone), $D = 32$ to 64 mm, $\phi' = 40^\circ$; and b) pebbles, $D = 16$ to 32 mm, $\phi' = 40^\circ$.	Continuation of work reported by Jansson, et al. (1948) with additional details and new test results. The ratio of wall displacement, measured at the mid-height of the wall, to wall height required to produce the active condition was 0.0003 for the macadam and about 0.001 for the pebbles. For both cases, $K_a \approx 0.2$, based on the assumption that the lateral earth pressure distribution is triangular. Other conclusions were similar to those of the earlier work by Jansson, et al. (1948).
Richard, O. D. 1965 and Linger, D. A.	8 ft. high x 8 ft. wide x 18 ft. long concrete box culvert, one side stiffer than the other, two backfill materials: a) select backfill (SW), $\phi = 43^\circ$, $c = 2.3$ psi; and b) uniform sand (SP), $\phi = 40^\circ$, $c = 0.6$ psi	Earth pressure cells were installed on the culvert and in the backfill to investigate the stress changes due to vehicle loads applied to the surface of the completed fill. Test results were compared with pressure changes calculated using Boussinesq's equation. Measured stress changes within the backfill generally agreed well with the theoretical values. Stress changes measured at the soil-structure interface were considerably higher than the theoretical values.
D'Appolonia, A. M. 1969 Whitman, R. V., and D'Appolonia, E. D.	Free-field stresses, compacted fill, poorly graded dune sand, $D_{50} \approx 0.18$ mm, $C_u \approx 1.5$	Measurements show that density and K_0 increase with increases in roller weight, operating frequency, and number of roller passes. Lateral stress on planes perpendicular to the roller path were higher than those on planes parallel to the roller path. Information on particle accelerations and peak dynamic stresses within the soil was also reported.

Table 2.3 Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Moore, P. J. 1972 and Spencer, G. K.</p>	<p>63 in. long x 19 in high model wall, instrumentation was on a 24 in. long central portion; Kaolin 37 backfill was placed behind the wall as a slurry and consolidated</p>	<p>Instrumentation included pressure cells and piezometers. Measured pore pressures during consolidation agreed well with theoretical values. K_0 after consolidation was measured as 0.51 and 0.57 for two tests. These agreed with lab K_0 tests that indicated $K_0 \approx 0.50$ to 0.55. In two tests, with high initial water content and no surcharge loading, wall movements away from the fill caused the lateral pressures to increase above their after consolidation values. Two tests, conducted with lower initial water contents and a surface applied surcharge, indicated a decrease in lateral pressure as the wall moved away from the soil. For the latter tests, after wall movements were stopped, the pressures typically returned to the at-rest values within 1 to 2 hours.</p>
<p>Rehman, S. E. 1972 and Broms, B. B.</p>	<p>600 cm long x 250 cm high test wall, two backfill materials: a) gravelly sand, and b) silty fine sand</p>	<p>The backfill was either placed loose or compacted in layers with a vibratory plate compactor. For the uncompacted soils the measured earth pressures were between the active case and the at-rest case for the gravelly sand and slightly below the active values for the silty sand. Measured pressures after compaction were greater than the pressures corresponding to $K_0 = (1 - \sin \phi')$ for the upper 0.5 to 1.5 m of the fill. Below these depths the pressures were approximately constant or slightly decreasing with depth, probably due to small deflections of the wall away from the fill as the upper layers were placed and compacted. The influence of surface loads on the lateral pressure on the wall were also investigated. Residual lateral pressures, after removal of the loads, were about 30% to 70% of the peak pressures induced by the loads.</p>

Table 2.3 Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Carder, D. R., 1977 Pocock, R. G., and Murray, R. T.</p>	<p>27 m long x 5 m wide x 3 m deep test bay, three 2 m x 2 m panels are located in the middle of one of the 27 m long walls, center panel contains most of the instrumentation, backfilled with a uniform washed sand, $D_{10} = .13$ mm, $C_u = 2.5$, $\phi = 39^\circ$</p>	<p>The sand was placed in 150 mm thick layers and compacted with a 1.3 Mg twin-roll vibrating roller. After compaction, lateral pressure in the upper 0.3 meters of fill corresponded to $\sigma_y(1/K_0)$ where $K_0 = (1 - \sin \phi')$. K was observed to be greater than $K_0 = (1 - \sin \phi')$ for depths less than about 1.5 m. Wall movement of $\Delta/H \approx 0.001$ away from the soil reduced the pressure to the fully active condition. Movement of $\Delta/H = 0.025$ toward the fill maximized the lateral force exerted on the wall. Wall displacements, Δ, were measured at the top of the wall.</p>
<p>Sherif, M. A. 1977 and Mackey, R. D.</p>	<p>1.2 m long x 1.2 m wide x .47 m high test bin, one side of the bin was instrumented, backfilled with uniform sand.</p>	<p>The magnitude of the increase in lateral pressure, due to a surface applied finite line load, was found to increase with the number of load application cycles.</p>
<p>Matsuo, M., 1978 Kenmochi, S., and Yagi, H.</p>	<p>10 m high x 6 m wide wall, the center section of the wall consisted of 5 panels; each 1 m wide x 2 m high panel was supported horizontally by 4 load cells; three backfill materials were used, a silty sand and two gradations of slag</p>	<p>The total lateral force calculated from the load cell readings, with no wall movement, corresponded to an earth pressure coefficient of 0.5 to 0.65 for all three materials. For the active condition, $K_a \approx 0.25$ for the silty sand and $K_a = 0.1$ to 0.25 for the slags. After the active condition was reached, the wall has kept stationary for a period of about 20 days. During this period the pressures increased steadily. For the active case, mobilized wall friction angles of about 50° were reported for all three backfills.</p>
<p>Smolczyk, U., 1979 Vogt, N., and Hilmer, K.</p>	<p>3.5 m long x 2.5 m high wall, sand backfill</p>	<p>The change in the lateral earth pressure on a wall due to surface applied line loads and small area loads was studied. The authors concluded that the recommendations of Terzaghi (1953) are valid.</p>

Table 2.3 Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Carder, D. R., 1980 Murray, R. T., and Krawczyk, J. V.</p>	<p>Same wall as Carder, et al. (1977), backfilled with silty clay, 82% passing #200 sieve, $\phi' = 37^\circ$, $c' = 0$, $\phi_U = 25 \text{ kN/m}^2$, $c_U = 13^\circ$, residual $\phi' = 33^\circ$</p>	<p>Fill was placed in layers and compacted by a 3.25 Mg smooth wheeled roller. The compacted lift thickness was 125 mm. Immediately after construction the lateral stresses were higher than those corresponding to $K_0 = (1 - \sin \phi')$. Four months after construction the pressure had decreased to approximately the at-rest condition. Outward wall movement of $\Delta/H = 0.009$ reduced the horizontal thrust to about 20% of the calculated active pressure resultant force. Subsequently, with no further wall movement, the measured thrust increased and after about two days, its value corresponded to the theoretical active case.</p>
<p>Sherif, M. A., 1982 Ishibashi, I., and Lee, C. D.</p>	<p>6 ft. long x 8 ft. wide x 4 ft. high test bin, instrumented part of 6 ft. x 4 ft. wall is 40 in. long x 41 in. high, backfilled with dry Ottawa sand, $e_{\max} = 0.754$ $e_{\min} = 0.530$</p>	<p>At-rest and active earth pressures under static and dynamic conditions were studied. It was suggested that the active condition should be defined as the condition when the mobilized wall friction angle is maximized. Densification by vibration increased the at-rest earth pressure and raised the point of application of the resultant.</p>
<p>Sherif, M. A., 1984 Fang, Y. S., and Sherif, R. I.</p>	<p>Same test facility and backfill as Sherif, et al. (1982)</p>	<p>Static at-rest and active earth pressures (rotation about base of wall) were studied. Conclusions were: 1) Jaky's equation for at-rest pressure is valid for loose sand, and 2) the at-rest pressure for dense sand is a function of the friction angle, the minimum density, and the actual density of the backfill.</p>
<p>Fang, Y. S. 1986 and Ishibashi, I.</p>	<p>Same test facility and backfill as Sherif, et al. (1982)</p>	<p>The variation of active earth pressure with depth was found to be nonlinear. For rotation about the top of the wall, the measured lateral thrust was about 17% greater than that predicted by Coulomb's method. The fully active state was reached at $\Delta/H \approx 0.0002$ to 0.0004 independent of the mode of deformation, where Δ is the movement of the top of the wall.</p>

Table 2.3 Cont.) Summary of Experimental Investigations of Earth Pressures - Model Studies.

REFERENCE	TEST FACILITY AND SOIL	PRINCIPAL STUDIES AND FINDINGS
<p>Frydman, S. 1987 and Ketissar, I.</p>	<p>Centrifuge model tests, 100 mm long x 20 to 210 mm wide (depending on test) x 195 mm high sample, 100 mm long x 195 mm high instrumented wall, uniform sand backfill, $D = 0.1$ to 0.3 mm, $C_u = 1.5$, $\phi' = 36^\circ$, $\delta' = 20^\circ$ to 25°</p>	<p>The model retaining wall was located close to a rigid boundary. Experimental data agreed well with the equation for pressure in silos, based on arching theory, presented by Janssen (1895).</p>
<p>McGown, A., 1987 Andrawes, K. Z., and Murray, R. T.</p>	<p>1 m high x .45 m wide wall, made up of 20 segments, each 50 mm high and supported laterally by a spring loaded shaft, backfilled with Leighton Buzzard sand, $D_{50} = 0.85$ mm, $C_u = 1.24$, $\gamma = 1.73$ t/m³, $\phi = 49.5^\circ$ from shear box tests</p>	<p>The wall stiffness was changed by changing the stiffness of the springs supporting the individual sensing panels. Tests with three different spring stiffnesses were compared to tests where the panels were rigidly supported for unreinforced and reinforced backfills. In all cases, reduced stiffness of the wall resulted in reduced pressure on the wall. It was suggested that the use of a compressible material on the back of the wall could be used to limit the earth pressure exerted on the wall.</p>

wall and the backfill material, and a summary of the principal studies and findings.

Several of these studies are reviewed in greater detail in the following sections. Each investigation reviewed in detail was chosen for one or more of the following reasons: 1) the model wall was large enough to represent field compaction without significant scale effects, 2) it contained exceptionally well-documented information on the relationship between wall movement and the lateral earth pressure and/or the wall-backfill interface friction coefficient, or 3) it provided exceptionally well-documented evidence relating to pressures due to surcharge loads, pressures induced by compaction, or pressure changes with time.

2.3.1 Terzaghi (1934a and 1934b)

Karl Terzaghi authored a series of articles related to earth pressures on retaining structures that were published in Engineering News Record in 1934. He developed a large earth pressure testing machine (Terzaghi, 1932) to provide experimental data useful for evaluating the design earth pressure for a 170 ft. high retaining wall at Fifteen-Mile Falls Dam.

The test bin, shown in Figure 2.25, was 14 ft. by 14 ft. in plan view with a 14 ft. long by 7 ft. high wall that was supported vertically at two points and horizontally at four points. The reaction forces at the wall support points were measured with mechanical scales.

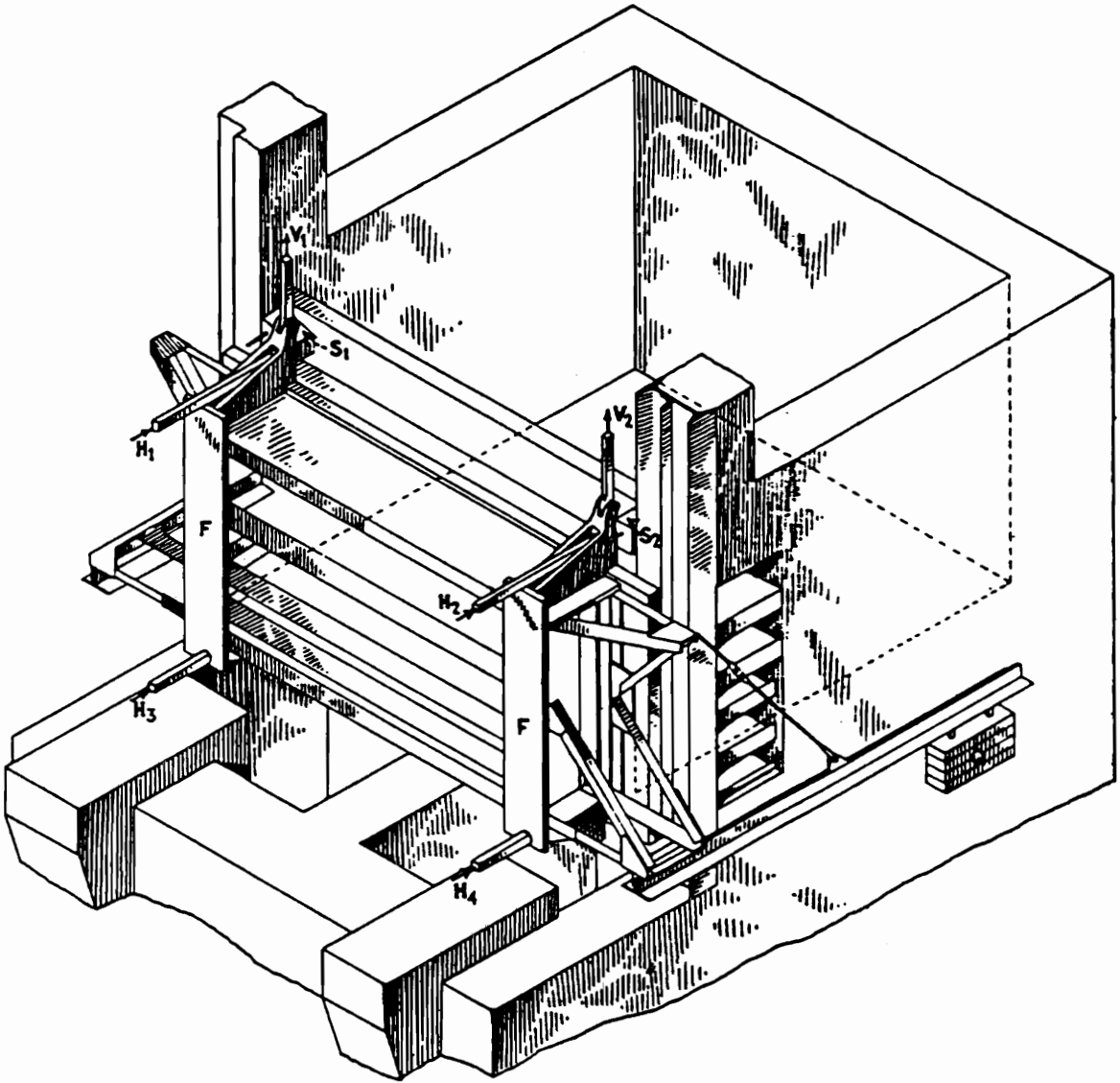


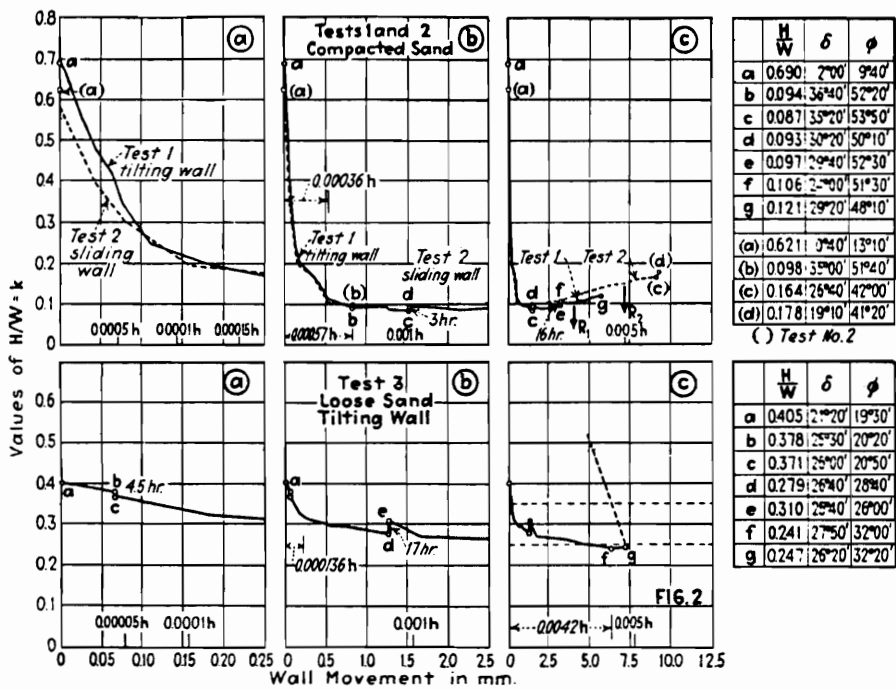
Figure 2.25) Earth Pressure Test Facility (Terzaghi, 1932).

The results of experimental studies using this facility were presented by Terzaghi (1934a and 1934b), and are reviewed in the following sections.

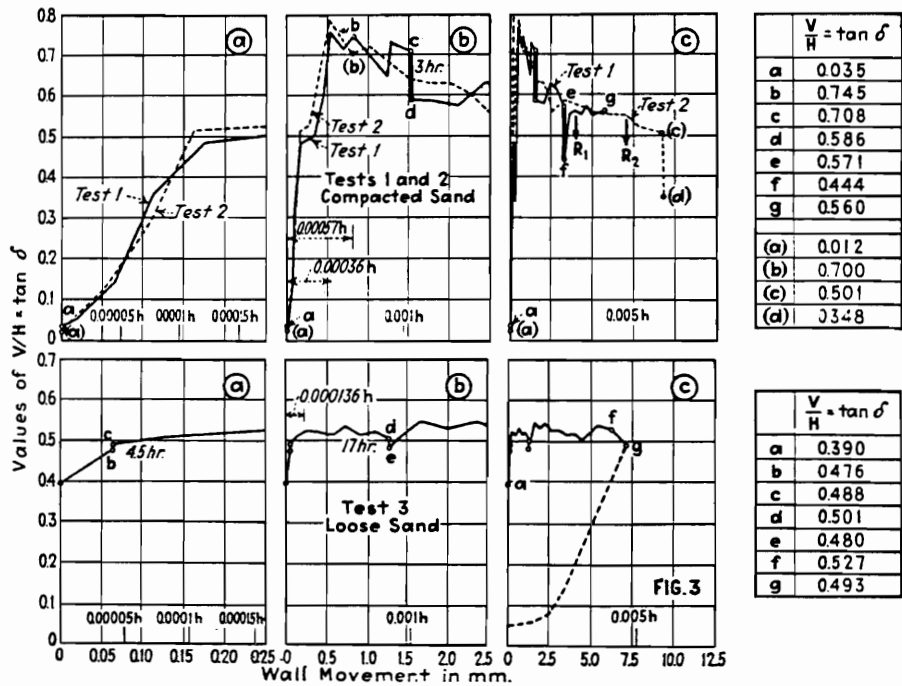
Terzaghi (1934a) presented the results of four tests conducted with dry sand to determine the effect of compaction and wall movement on the earth pressure. The backfill material was a uniform, medium, angular sand with $D_{10} = 0.54$ mm.

Figure 2.26a shows the lateral earth pressure coefficient, based on the measured horizontal forces, as a function of wall movement for tests 1 through 3. The data are presented with three graphs for each test. A different horizontal scale is used for each of the three graphs (a, b, and c). During the tests the wall was moved away from the backfill. The movements were translational for test 2 and rotational for tests 1 and 3. Prior to wall movement, the lateral earth pressure coefficient, K , was 0.62 and 0.70 for the two tests with dense sand and 0.40 for the test with loose sand. Based on earlier tests, Terzaghi reported that the lateral earth pressure coefficient for compacted backfills ranged from 0.35 to 0.70 depending on the method of compaction.

The results of tests 1 and 2 indicate that for compacted sand the minimum earth pressure coefficient and the average wall movement required to reach the minimum value are similar for rotational and translational wall movements. The wall movements reported in Figure 2.26 were measured at the mid-height of the wall. For the compacted sand, wall movements of 0.20 mm away from the backfill reduced the earth



a) lateral earth pressure coefficient



b) wall friction coefficient

Figure 2.26) Measured Lateral Earth Pressure Coefficient and Wall Friction Coefficient for Dry Sand (Terzaghi, 1934a).

pressure coefficient to 0.2, and the minimum value of $K = 0.1$ corresponded to a wall movement of about 0.8 mm.

Test 3 showed that for a loose sand backfill and a wall rotated about its base, a mid-height displacement of about 5.0 mm was required to reduce K to its minimum value of about 0.25.

Figure 2.26b shows the wall friction coefficient, $\tan \delta$, as a function of wall movement for tests 1 through 3. The value of $\tan \delta$ corresponding to the active case ranged from about 0.4 to about 0.8.

Terzaghi (1934b) presented the results of a test using the same test facility and backfill sand to determine the effects of backfill saturation and water pressure on the pressures exerted on the wall. Based on this test and the results of tests reported by Terzaghi (1934a), Terzaghi concluded: 1) the total lateral pressure of a submerged fill is the sum of the water pressure and the soil pressure, and 2) the presence of water has little effect on the internal friction angle of the soil and the wall friction angle.

2.3.2 Spangler and Mickle (1956)

Spangler and Mickle (1956) presented the results of research conducted at the Iowa Engineering Experiment Station. The results of earlier studies of the lateral earth pressure due to point, line, and strip loads, reported by Spangler (1938 and 1939), were reviewed and new data on the lateral earth pressure due to uniformly loaded finite areas were presented.

The retaining wall used for the initial studies was a 6 ft. high reinforced concrete cantilever wall. The backfill was a pit-run gravelly sand placed by hand without compaction. Two systems were used to measure the earth pressures: 1) stainless steel friction ribbons and 2) Goldbeck earth pressure cells.

The results of a series of tests conducted to measure the lateral pressure due to a surface applied concentrated load are shown in Figure 2.27. A wheel load of about 10.5 kips was applied to the surface of the fill. The results are presented as the change in lateral pressure per kip of surface applied vertical point load. The data are scattered, but Spangler and Mickle found that in general they could be represented by the equation:

$$h_c = P \frac{x^2 z}{R^5} \quad \text{Eqn. 2.1}$$

where: h_c = horizontal pressure at a point on the wall due to a surface applied vertical point load,

P = vertical point load applied to the surface of the fill,

x , y , and z = the coordinates of the point on the wall where h_c is being calculated, and

R = the distance from the point load to the point on the wall
 $= \sqrt{x^2 + y^2 + z^2}$.

The pressures calculated using Equation 2.1 are approximately two times those calculated using the Boussinesq equation for horizontal stress within a semi-infinite elastic half space due to a surface

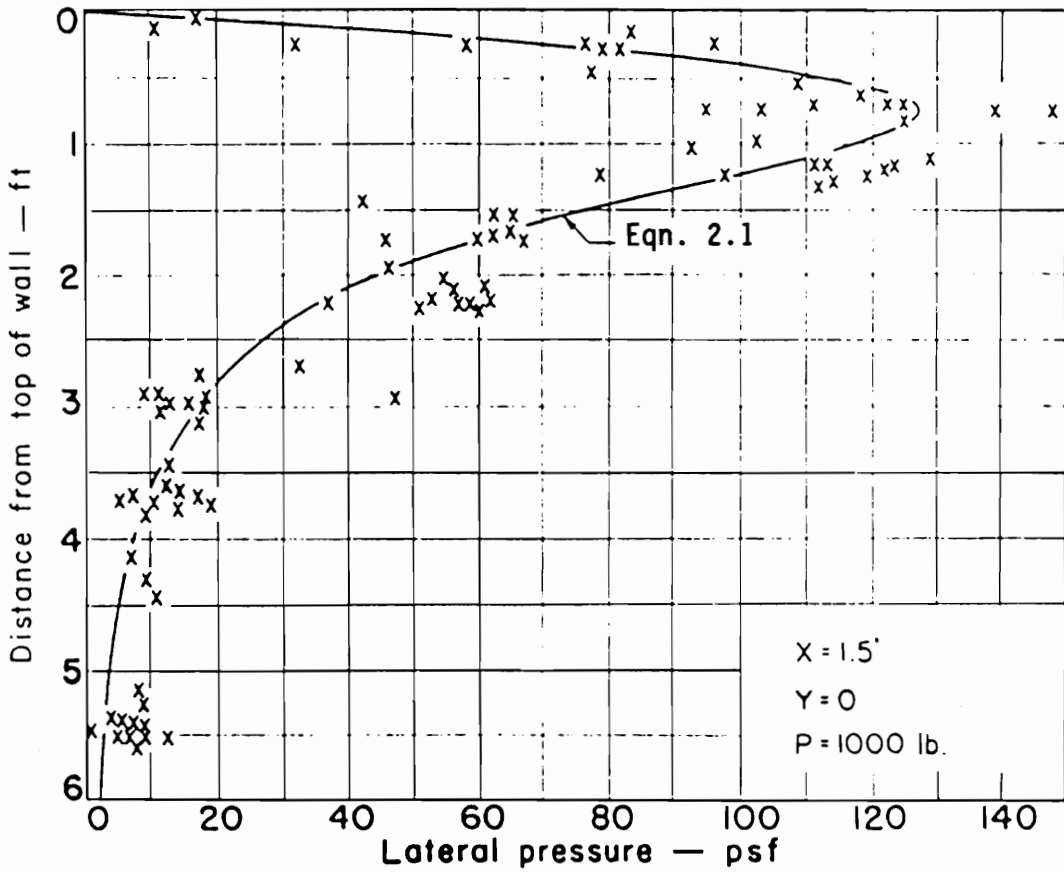


Figure 2.27) Lateral Earth Pressures on a Retaining Wall Due to a Point Load on the Surface of the Fill (Spangler and Mickle, 1956).

applied concentrated load with Poisson's ratio equal to 0.5.

The results of measurements of the lateral pressure induced by a 10.08 ft. long narrow strip load are shown in Figure 2.28. Spangler and Mickle integrated Equation 2.1 between the limits $+\infty$ and $-\infty$ and found:

$$h_1 = 1.33 P_1 \frac{x^2 z}{R_1^4} \quad \text{Eqn. 2.2}$$

where: h_1 = horizontal unit pressure at a point on the wall due to an infinitely long line load,

P_1 = vertical load per unit length,

x and z = the coordinates of the point on the wall where h_1 is being calculated, and

R_1 = the distance from the line load to the point on the wall
 $= \sqrt{x^2 + z^2}$.

They also integrated Equation 2.1 between the limits y_1 and $-y_2$ to provide an equation for the pressure due to a finite length uniform line load placed parallel to the wall. The resulting equation was simplified for the specific case of y_1 equal to y_2 , thus providing an expression for the lateral stress on the wall at points that are opposite the midpoint of the line load:

$$h_1 = \frac{2}{3} P_1 \frac{x^2 z}{R_1^4} \left[\frac{R_1^2 y_1}{(R_1^2 + y_1^2)^{1.5}} + \frac{2 y_1}{(R_1^2 + y_1^2)^{0.5}} \right] \quad \text{Eqn. 2.3}$$

where : y_1 = one half of the length of the line load,

h_1 = horizontal unit pressure due to a vertical line load, at

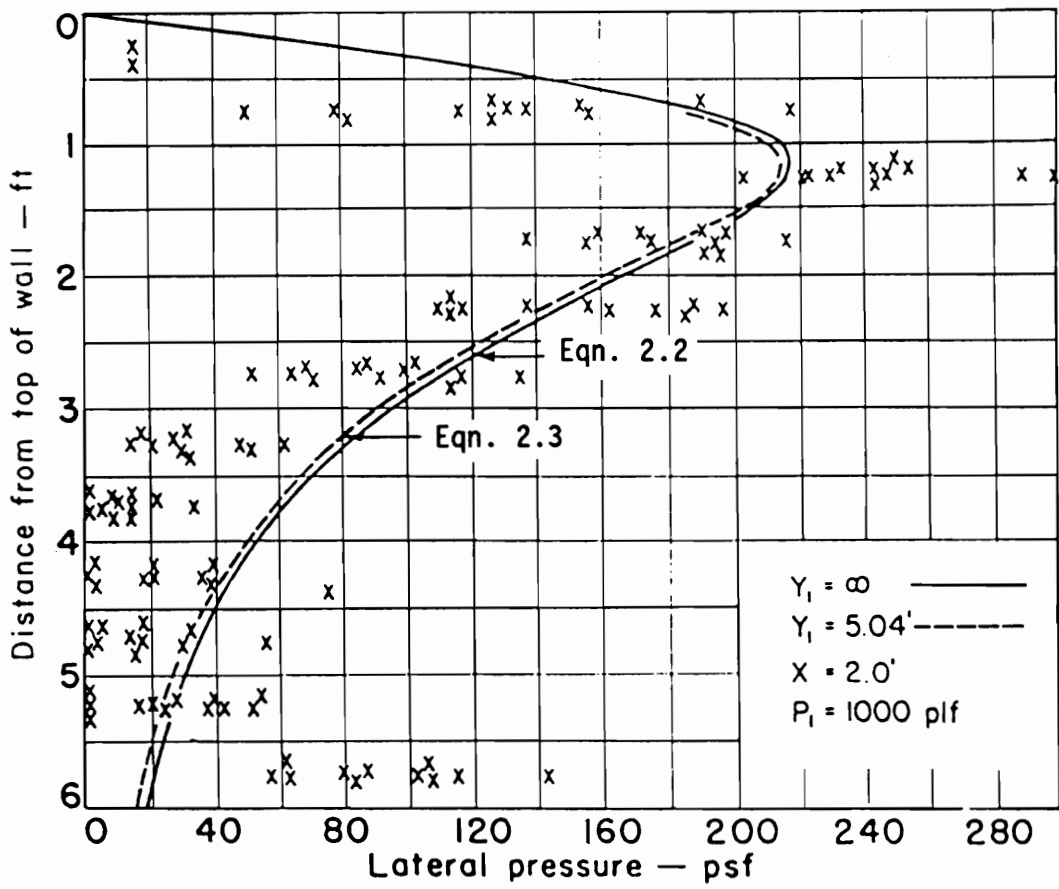


Figure 2.28) Lateral Earth Pressures on a Retaining Wall Due to a Narrow Strip Load on the Surface of the Fill (Spangler and Mickle, 1956).

a point on the wall that is opposite the midpoint of the line load, and

P_1 , R_1 , x , and z are as previously defined.

Equation 2.2 is approximately twice the Boussinesq solution for an infinitely long line load parallel to the wall and Equation 2.3 is approximately twice the Boussinesq solution for a finite length line load parallel to the wall. The two equations, as shown in Figure 2.28, are in general agreement with the experimental data.

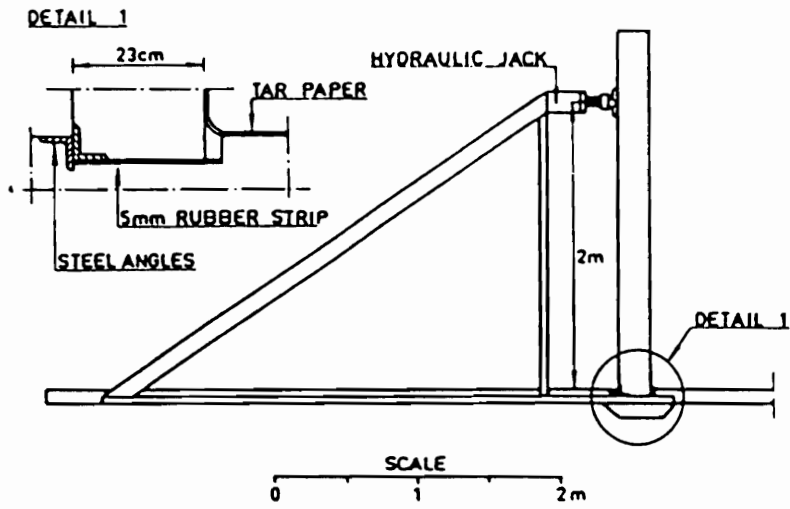
The results of other tests indicated similar agreement, between the experimental data and twice the Boussinesq equation, for lateral stresses due to uniformly loaded finite areas.

Spangler and Mickle reported that after removal of the surface applied loads there was often a residual effect due to the applied loads and the lateral stresses did not return to the values measured prior to loading.

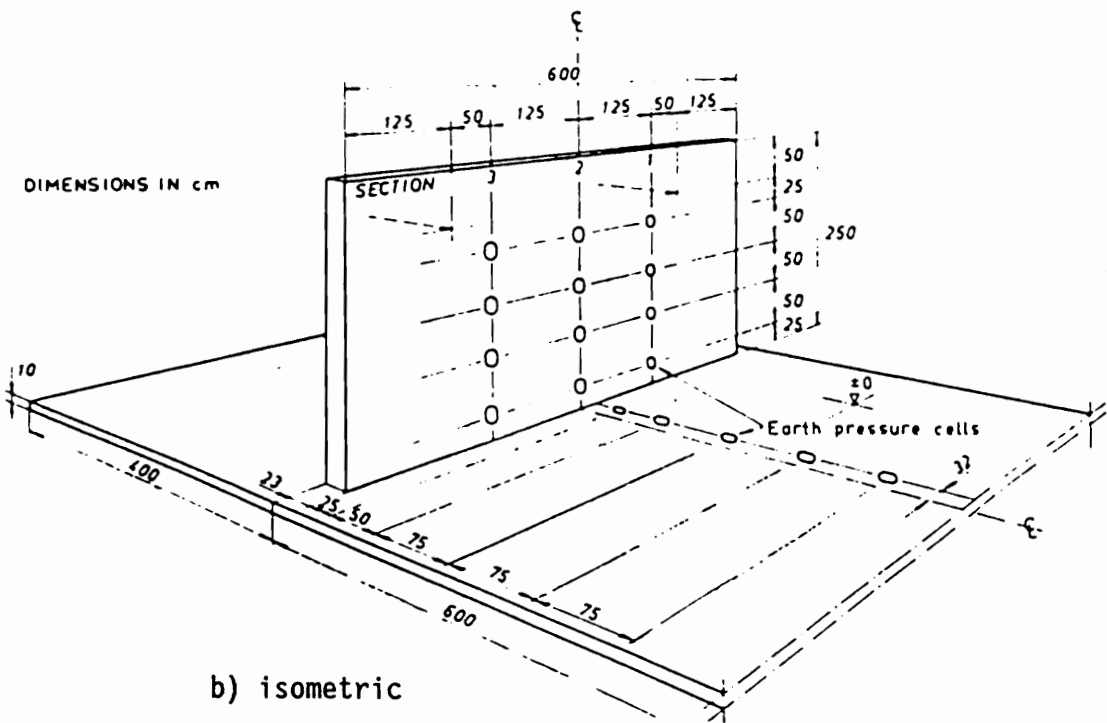
2.3.3 Rehnman and Broms (1972)

Rehnman and Broms (1972) used an instrumented wall system to investigate lateral earth pressures. The wall was 2.5 m high and 6 m long. Figure 2.29 shows an isometric view and a cross section of the wall system.

Earth pressures were measured by seventeen Gloetzl earth pressure cells. Twelve cells were mounted on the wall to measure lateral earth pressures and five cells were mounted on the floor slab to measure the distribution of the overburden pressure. The wall could be rotated



a) cross section



b) isometric

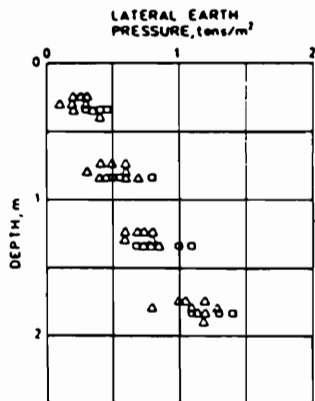
Figure 2.29) Experimental Retaining Wall (Rehman and Broms, 1972).

about its base using hydraulic jacks and displacements were measured using twelve dial gauges with an accuracy of 0.01 mm.

Two backfill materials were used: 1) a gravelly sand and 2) a silty fine sand. Both materials were placed loosely and with compaction. Compaction of the gravelly sand was either in 40 cm thick layers with a 400 kg vibratory plate compactor or in 20 cm thick layers with a 140 kg vibratory plate compactor. The silty fine sand was compacted with the 400 kg compactor using 20 cm thick layers. For some of the tests, the back of the wall was covered with 50-mm-thick Rockwool insulation mats.

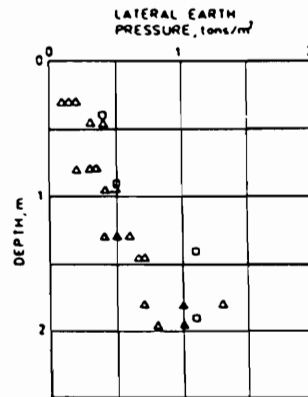
Measured earth pressures for both backfill materials, placed with and without compaction, are shown in Figure 2.30. The measured pressures for the loose backfills are shown in Figure 2.30a for the gravelly sand and in Figure 2.30b for the silty fine sand. For the loose condition, the measured pressures can be represented by earth pressure coefficients of about 0.35 for the gravelly sand and about 0.31 for the silty fine sand. For both backfill materials, compaction with a 400 kg vibratory plate produced higher pressures on the upper part of the wall, and lower pressures near the bottom of the wall, than those recorded for the loose backfills.

The relatively high pressures measured near the top of the wall for the compacted backfills may indicate the existence of residual stresses due to compaction. As the upper layers of the backfill were compacted, the high lateral stresses most likely caused displacement of the wall away from the backfill. Movement of the wall away from the previously compacted backfill may have reduced the pressures on the wall and may



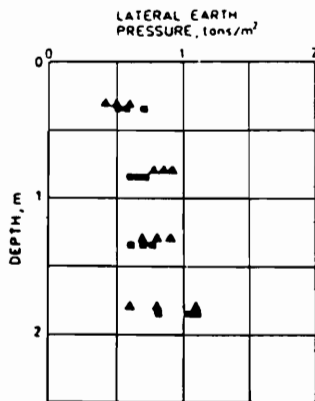
LEGEND
 Without insulation mats: Δ
 With insulation mats: \square

a) loose gravelly sand



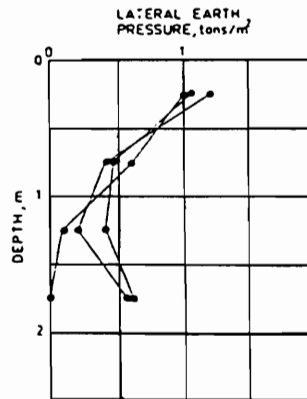
LEGEND
 Without insulation mats: Δ
 With insulation mats: \square

b) loose silty fine sand



LEGEND
 Without insulation mats: Δ
 With insulation mats: \square
COMPACTION
 400kg vibratory plate-
 compactor
 40cm layer thickness

c) compacted gravelly sand



COMPACTION
 400kg vibratory plate
 compactor
 20cm layer thickness

d) compacted silty fine sand

Figure 2.30) Measured Earth Pressures (Rehman and Broms, 1972).

account for the lower than expected pressures on the bottom half of the wall.

Rehman and Broms also studied the increase in lateral earth pressure due to loads applied to the surface of the backfill. The data from these tests contained considerable scatter. However, fair qualitative agreement with the Boussinesq theory was noted. The stress increases were greater for the loose backfills than for the compacted backfills. After removal of the surcharge loading, about 60% to 70% of the stress due to the surcharge remained.

2.3.4 Carder, Pocock, and Murray (1977)

Carder, et al. (1977) investigated the lateral earth pressure of a sand using a large model wall facility at the Transport and Road Research Laboratory at Crowthorne, Berkshire, England. Active, at-rest, and passive pressures were studied.

The experimental retaining wall facility consisted of a massive trough-shaped concrete structure with a movable metal wall as shown in Figure 2.31. The metal wall was supported horizontally and vertically by load cells and could be moved toward or away from the backfill using a jacking system. Wall movements could be translational or rotational.

The earth pressures on the concrete wall and the movable metal wall were measured using 36 earth pressure cells. Three types of earth pressure cells were used: 1) hydraulic, 2) pneumatic, and 3) strain gaged. Details of the pressure cells and the calibration procedures were reported by Carder and Krawczyk (1975).

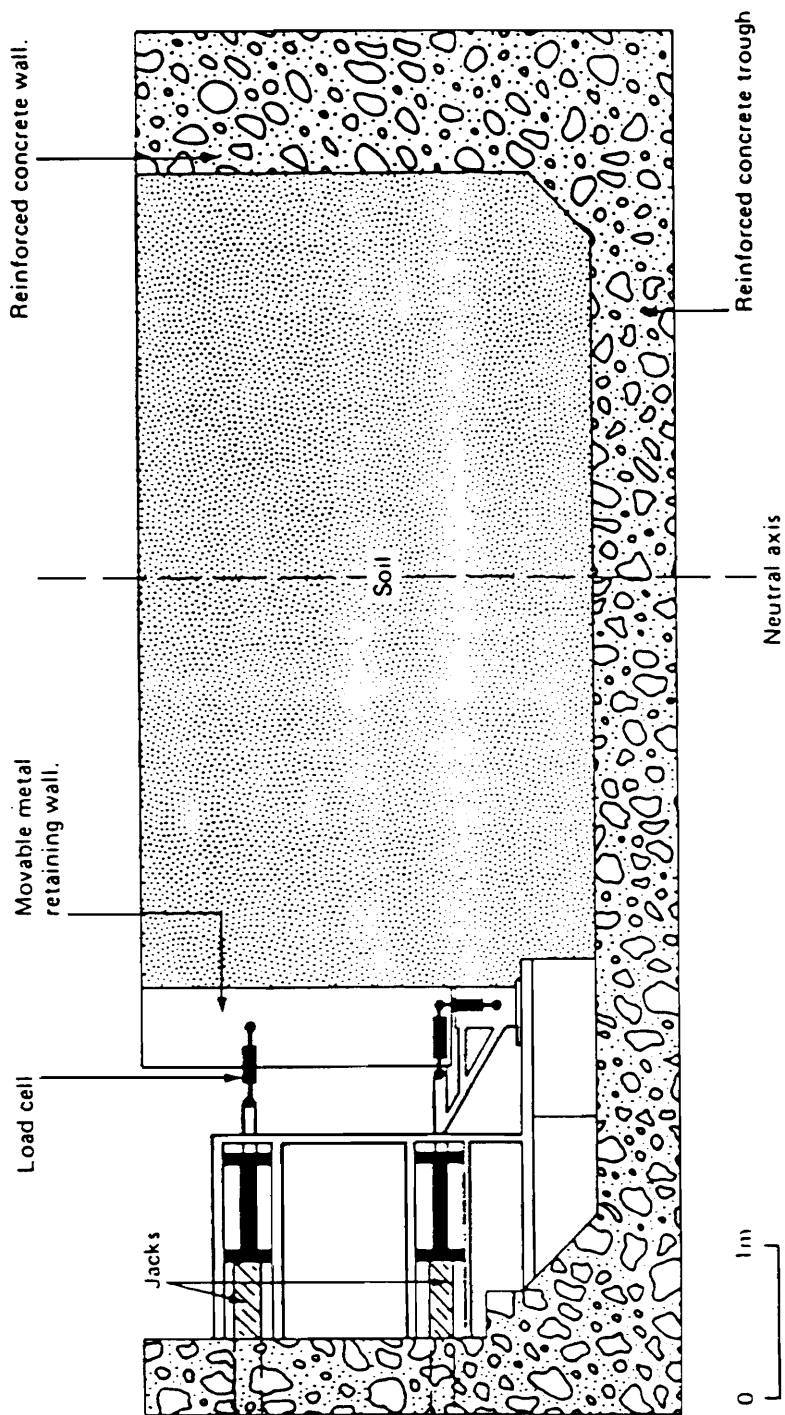


Figure 2.31) Experimental Retaining Wall Facility, Transport and Road Research Laboratory (Carder, et al., 1977).

The washed uniform sand backfill was spread in 0.15 m thick layers and compacted by six passes of a 1.3 Mg vibratory roller. The compacted bulk density was 2.0 Mg/m^3 and the moisture content was about 10 percent.

Figure 2.32a shows the earth pressures measured after compaction for experiments 1 and 2. Figure 2.32b shows the measured earth pressures on the concrete wall and on the metal wall for experiment 2. For reference, the figures include lines representing $K_0\sigma_v$ and $K_0^1\sigma_v$, where $K_0 = 1 - \sin \phi'$ and $K_0^1 = 1/K_0$. The measured earth pressures exceeded the at-rest earth pressures at most gage locations. Near the surface of the fill, the measured pressures were close to the K_0^1 line, which represents an approximate upper limit for the horizontal pressure. After departure from the K_0^1 line, the measured pressures are nearly constant with increasing depth. The higher than at-rest pressures near the surface indicate residual compaction stresses.

After the at-rest earth pressures were recorded, a uniform surcharge load of 27 kPa, which corresponds to 1.4 m of fill, was applied to the surface of the backfill. With the surcharge in place, the wall was translated away from the backfill. Figure 2.33 shows the measured horizontal and vertical forces on the wall as a function of wall movement. The minimum values of both forces correspond to a wall movement of about 4 mm away from the backfill.

An investigation of the development of passive pressures was conducted with a 1 m thick fill without surcharge. The maximum lateral force was developed after the wall was moved about 25 mm toward the

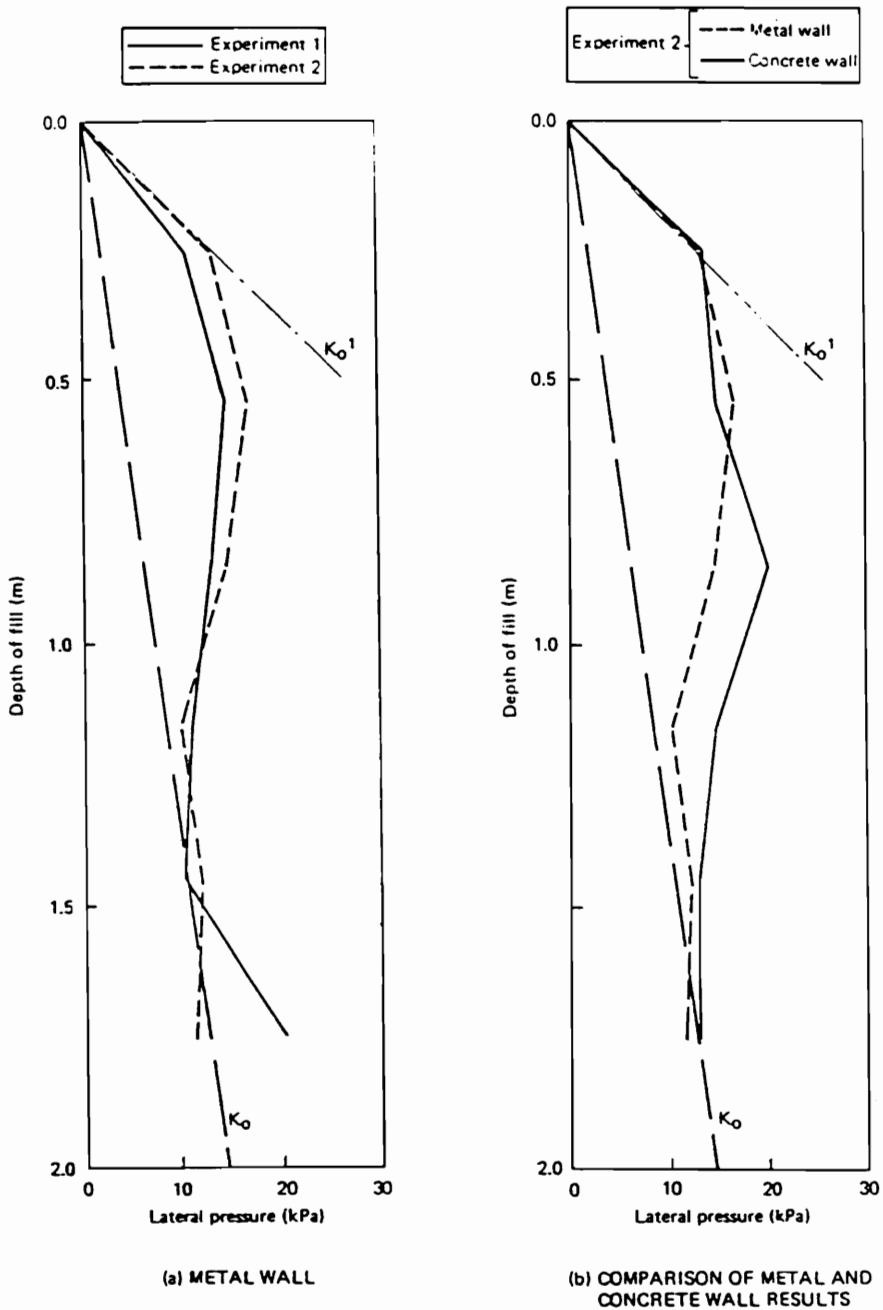


Figure 2.32) Measured Earth Pressures for a Sand Backfill, TRRL Wall (Carder, et al., 1977).

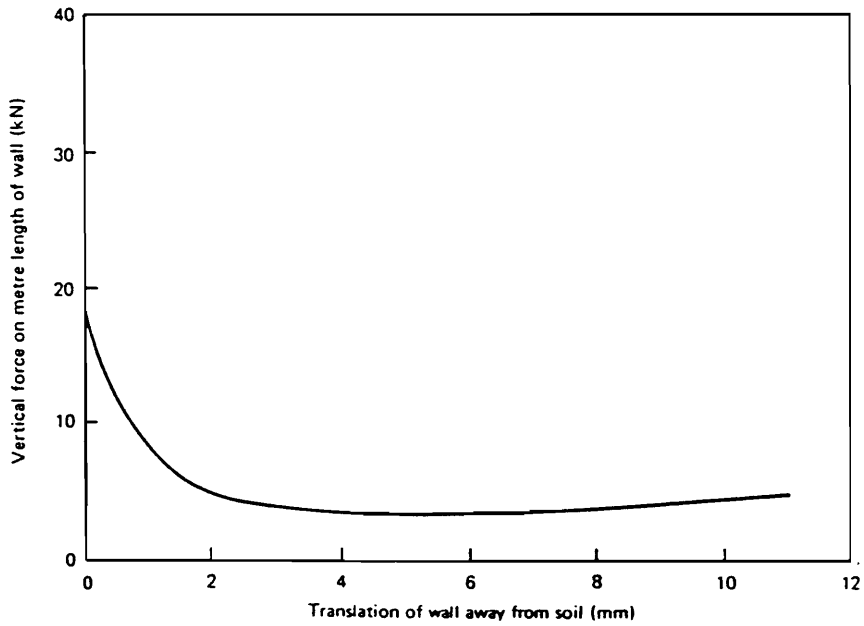
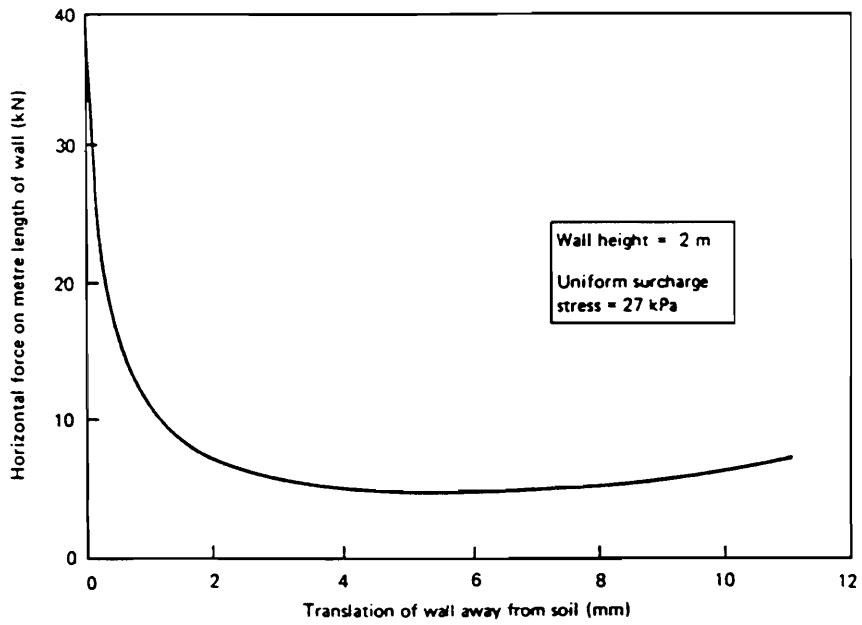


Figure 2.33) Measured Vertical and Horizontal Forces with the Wall Translating Away from the Fill (Carder, et al., 1977).

backfill. The maximum force corresponded to an earth pressure coefficient of about 10, which is slightly higher than the value of 7.9 calculated by Carder, et al., using Coulomb's theory with an assumed wall friction angle of 15°.

2.3.5 Carder, Murray, and Krawczyk (1980)

Carder, et al. (1980) used the same facility as Carder, et al. (1977) to study the earth pressure of a silty clay backfill. The instrumentation system for this study included piezometers to monitor the pore pressures.

The backfill material was a silty clay with a liquid limit of 42.5 percent and a plastic limit of 17.0 percent. The drained strength parameters of $\phi' = 37^\circ$ and $c' = 0$ and the undrained strength parameters of $c_u = 25 \text{ kN/m}^2$ and $\phi_u = 13^\circ$ were determined for the silty clay based on triaxial tests. The backfill was spread and compacted to 125 mm thick layers by six passes of a 3.25 Mg smooth wheeled roller. The average compacted bulk density was 2.0 Mg/m^3 at an average water content of 18.5 percent.

The pressures measured on the concrete wall and the metal wall immediately after construction are shown in Figure 2.34. The measured pressures on the concrete wall were generally higher than those measured on the metal wall. For both walls, the measured pressures in the upper meter of the fill were significantly higher than those corresponding to $K_0\sigma_v$ where $K_0 = 1 - \sin \phi'$.

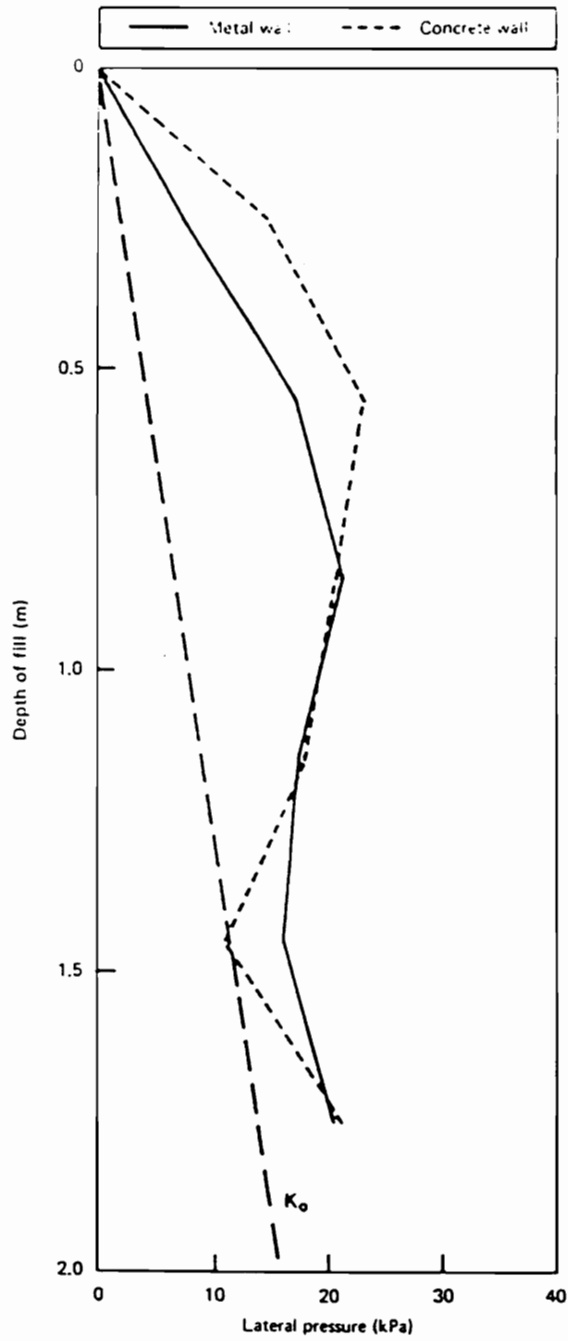


Figure 2.34) Measured Earth Pressures for a Silty Clay Backfill, TRRL Wall (Carder, et al., 1980).

The pressures were monitored for a period of 120 days. Figure 2.35 shows the total lateral force as a function of time and indicates a significant reduction in the lateral force over the 120 day observation period. The pressure distribution observed at the end of the 120 day period was close to that calculated for the at-rest case.

2.4 LABORATORY STUDIES OF AT-REST EARTH PRESSURES

The ratio of horizontal earth pressure to vertical earth pressure under the condition of zero lateral strain is referred to as the at-rest earth pressure coefficient, K_0 . Although there are few cases in practice where the retaining structure is rigid enough to maintain a condition of zero lateral strain, K_0 test data provide useful information about the relationship between the horizontal and vertical pressures in the soil under simple and clearly defined boundary conditions.

The value of K_0 for soils has been investigated by a number of researchers in an effort to determine the factors that influence its value and to establish empirical formulas that can be used to estimate K_0 based on other soil parameters. Table 2.4 summarizes the previous experimental studies of K_0 . Each entry in the table contains the source of information, the type of apparatus used, and the number of load-unload cycles applied to the specimen. The types of apparatus used in these studies and the findings are discussed in the following sections.

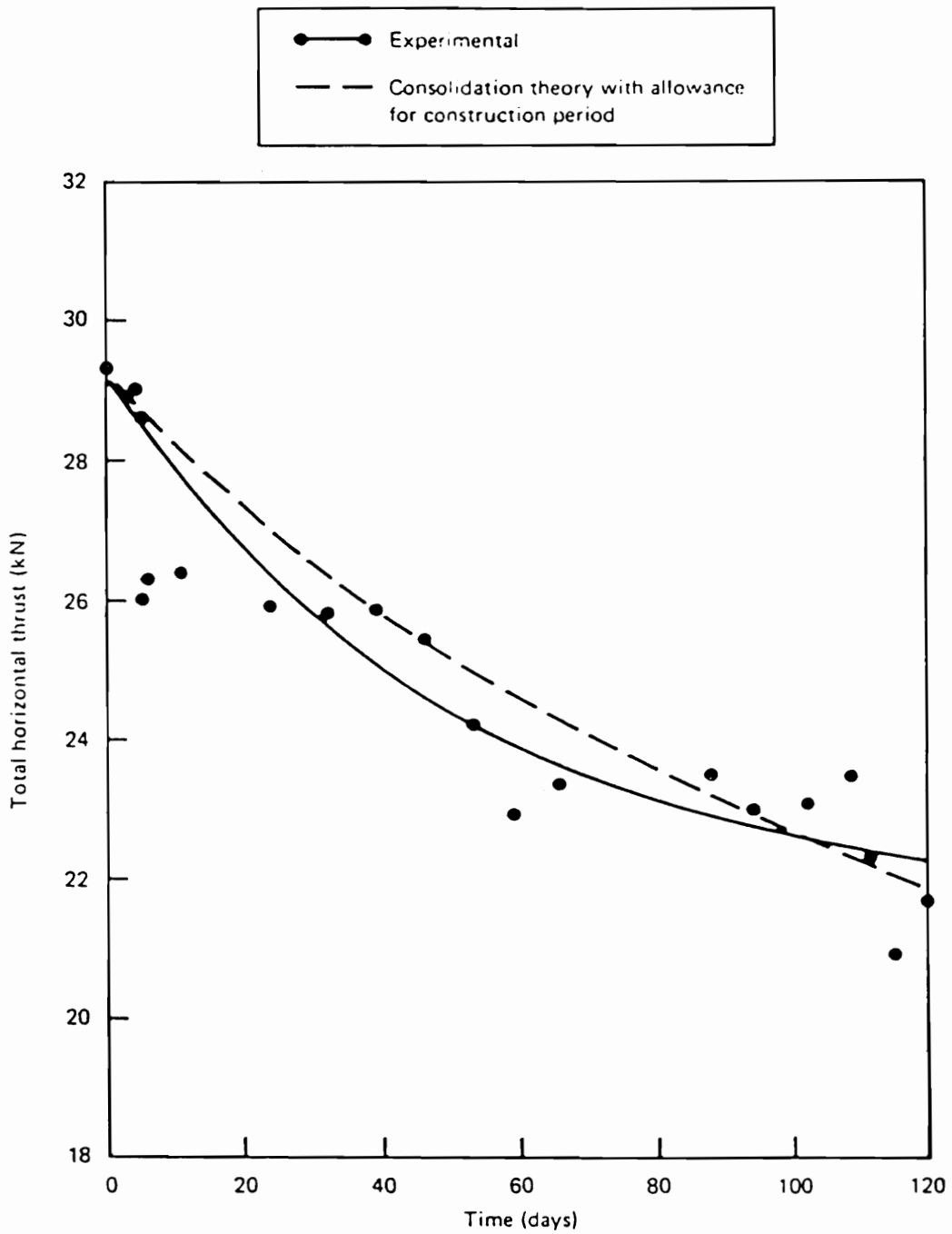


Figure 2.35) Decrease in Horizontal Thrust with Time for a Silty Clay, TRRL Wall (Carder, et al., 1980).

Table 2.4) Summary of Laboratory Studies of At-Rest Earth Pressures.

Reference	Type of Apparatus	Tests
Terzaghi, 1920	Friction tape	Load only
Kjellman, 1936	Cubical triaxial	Load-unload
Binnie and Price, 1941	Oedometer	Load only
Bayliss, 1948	Earth pressure meter	Load only
Kjellman and Jakobson (1955)	Triaxial	
Bishop and Henkel, 1957	Triaxial	Load-unload
Bishop, 1958	Triaxial	Load-unload
Hsu Chi-in, 1958	Fluid-filled rubber chamber	Load only
Hendron, 1963	Oedometer	Load-unload
Brooker and Ireland, 1965	Oedometer	Load-unload
Akai and Adachi, 1965	Triaxial	Load only
Wright, 1969	Triaxial	Load-unload (3 cycles)
Obrcian, 1970	Oedometer	Load-unload (4 cycles)
Menzies, et al., 1977	Triaxial	Load only
Ofer, 1981	Oedometer	Load-unload (4 cycles)

2.4.1 Types of Equipment Used to Investigate K_0

The basic objective of K_0 testing is to determine the relationship between the horizontal and the vertical stress within a soil specimen under the condition of zero lateral strain (K_0 condition). The amount of lateral strain that can be allowed without significant deviation from the K_0 condition is about 10^{-5} to 10^{-6} (Bishop, 1958; Schmidt, 1967).

Several types of apparatus have been used to investigate the at-rest earth pressure coefficient, K_0 . The most common of these are triaxial tests and oedometer tests. Several other types of test have also been used. Each is discussed below.

2.4.1.1 K_0 Triaxial Equipment

Triaxial equipment for K_0 testing consists of a conventional triaxial cell equipped with a means of accurately measuring the diameter or the circumference of the specimen during the test. As the vertical stress on the sample is increased, the lateral deformation is monitored and kept very near zero by adjusting the lateral pressure. With this procedure, the relationship between the horizontal pressure and the vertical pressure is determined for the at-rest condition.

2.4.1.2 K_0 Oedometers

Instrumented oedometers are similar in principal to conventional oedometers used for one-dimensional consolidation testing in that they have sufficient rigidity to enforce the condition of zero lateral strain. The primary difference is that K_0 oedometers must have a

provision for measuring the lateral stress. Several approaches have been used to measure the lateral pressure:

- a) The wall of the oedometer has been thinned over a portion of its height and the oedometer placed inside a second tight fitting ring to produce a sealed annular cavity. The deflection of the thinned section of the oedometer is instrumented to measure its deflection. As the vertical load is applied, the deflection of the thinned section is monitored and kept very near zero by adjusting the pressure in the annular cavity. The at-rest horizontal pressure is the pressure required in the annular cavity to maintain zero deflection of the thinned section.
- b) An oedometer with a sealed annular cavity and a thin wall between the soil specimen and the cavity, as described above, has been used with the cavity filled with an incompressible fluid. The lateral pressure of the soil can be monitored by measuring the pressure of the fluid in the cavity. A pressure indicator with a high stiffness is required for this measurement.
- c) Oedometers have been split in half diametrically and instrumented to determine the force required to prevent relative movement between the two halves.

2.4.1.3 Other K_0 Testing Devices

Other equipment used to investigate the at-rest earth pressure coefficient include:

- a) friction tapes on the sidewall of a box filled with soil used to determine the lateral soil pressure,
- b) cubical triaxial equipment,
- c) earth pressure meter, and
- d) a fluid-filled rubber chamber.

2.4.2 Summary of Findings from Previous K_0 Studies

Mayne and Kulhawy (1982) compiled information from K_0 testing by several researchers on more than 170 different soils. They found that the equation $K_0 = 1 - \sin \phi'$ proposed by Jaky (1944) was supported by the experimental data for normally consolidated cohesive and noncohesive soils. For the first unload cycle, Mayne and Kulhawy (1982) found that the experimental data supported the equation $K_0 = (1 - \sin \phi') OCR^{\sin \phi'}$ proposed by Schmidt (1966), where OCR is the overconsolidation ratio.

2.5 SUMMARY

Experimental studies of earth pressures on retaining structures have been reviewed. The studies included earth pressure and wall deformation measurements on full scale field installations and on model walls. Several laboratory studies of the at-rest lateral earth pressure coefficient were also reviewed. A summary of the studies reviewed was presented in Table 2.1, Summary of Experimental Investigations of Earth Pressures - Field Studies, Table 2.3, Summary of Experimental Investigations of Earth Pressures - Model Studies, and Table 2.4, Summary of Laboratory Studies of At-rest Earth Pressures.

The findings of the studies include:

- 1) The amount of wall deflection required to reach the active pressure condition has been studied by many researchers. In general, they found that the deflection required to reach the active condition depends on the properties of the backfill material. For loose sands, Terzaghi (1934a) found that $\Delta/H = 0.008$, where Δ is the displacement of the wall measured at mid-height, was required to reduce the earth pressure to its minimum value. Fang and Ishibashi (1986) reported that a deflection of the top of a 3.3 ft. high wall corresponding to $\Delta/H = 0.0003$ was enough to reduce the lateral earth pressure of a medium dense sand to its minimum value.
- 2) For loose cohesionless backfills, Sherif, et al. (1984) found that the measured earth pressures on a stiff non-yielding wall could be represented by the at-rest earth pressure coefficient calculated using the equation $K_0 = 1 - \sin \phi'$ suggested by Jaky (1944).
- 3) Compaction of the backfill near stiff structures can produce lateral pressures greater than those corresponding to $K_0 = 1 - \sin \phi'$ in the upper part of the backfill. Vaughan and Kennard (1972) reported $K = 0.72$ for a boulder clay backfill placed against a concrete dam. Terzaghi (1934a) reported $K = 0.35$ to 0.70 for compacted backfills, depending on the method of compaction.
- 4) Field studies by Goldbeck (1938), Bruner, et al. (1983), and McCann, et al. (1987) showed that compaction of the backfill behind a yielding retaining structure can produce lateral pressures after construction that are near the at-rest pressures, even though the

observed movement of the structure is greater than what is normally expected to reduce the pressures to the active condition.

- 5) Lateral pressures near the surface of compacted backfills are limited by the strength of the backfill and the vertical overburden pressure. Theoretically, the maximum horizontal pressure that can exist in the backfill without failure of the soil is $\sigma_H = \sigma_V \tan^2(45 + \phi'/2)$. Measurements by Carder, et al. (1977) illustrate the limit of the lateral earth pressure near the backfill surface.
- 6) Studies by Rehman and Broms (1972), Bruner, et al. (1983), and Carder, et al. (1977) indicate that compaction of the upper layers of the backfill can cause deformation of the retaining structure away from the backfill. Lateral pressures in previously compacted layers may decrease as a result of these deflections.
- 7) In addition to increasing the lateral pressures, compaction can produce larger than expected lateral deformations. Ingold (1979a) reported a case history where compaction of the backfill behind a 14 ft. high wall caused the top of the wall to move 3.7 inches outward ($\Delta/H = 0.02$) during construction. Excavation of the backfill revealed a horizontal tension crack on the backfill side of the wall stem near its base.
- 8) Settlement of the backfill with respect to the retaining structure is caused by the increasing vertical pressure resulting from the placement and compaction of additional layers of backfill. The relative movement between the soil and the structure produces

downward shear forces on the structure. Data reported by Terzaghi (1934a), Kany (1972), Fukuoka and Imamura (1984), and Vogt, et al. (1986) indicate that the interface friction coefficient ranges from about 0.35 to about 0.90. The data reported by Vogt, et al. (1986) represent an observation period of almost six years, indicating that shear forces persist over a long period.

- 9) Earth pressures from clay backfills are time dependent. Moore and Spencer (1972) reported that after a model wall backfilled with clay had been moved far enough to produce the active pressure condition, and it was subsequently held stationary, the earth pressures returned to the at-rest pressures within 1 to 2 hours. Carder, et al. (1980) found that the lateral pressures from a compacted clay backfill were high immediately after construction, but decreased to values corresponding to the at-rest pressures over a period of 120 days.
- 10) The lateral earth pressures due to various surcharge loads applied to the surface of the backfill were studied by Spangler (1938 and 1939), Spangler and Mickle (1956), Richard and Linger (1965), Rehnman and Broms (1972), and Jansson, et al. (1948). In general, these studies indicate that the lateral pressure on stiff retaining structures due to surcharge loads can be approximated by two times the value calculated using solutions based on Boussinesq's equation for lateral stress within a semi-infinite elastic half-space.
- 11) Studies by Spangler and Mickle (1956), Rehnman and Broms (1972) and Jansson, et al. (1948) indicated that about 30 to 70 percent of the

pressure due to surcharge loads remains as a residual pressure after the surcharge load has been removed.

- 12) D'Appolonia, et al. (1969) measured free-field horizontal pressures due to compaction and found that the horizontal pressures in the direction of the roller travel were greater than those in the direction normal to the path of the roller.
- 13) Interpretation of the lateral pressures reported in the literature is often difficult because of the uncertainties about the accuracy of the measurements and the scatter common to earth pressure measurements. The measured earth pressure values may be influenced by many factors, including: a) construction procedures, b) the changing properties of the backfill material as it is being compacted, c) instrument and calibration errors, and d) external factors such as temperature, nearby construction activities and traffic, and deformations caused by connected structural elements. A number of factors associated with instrument accuracy and calibration procedures have been identified by Weiler and Kulhawy (1982), Krizek, et al. (1974), and Hvorslev (1976).
- 14) Mayne and Kulhawy (1982) have shown that for the first load-unload cycle the at-rest lateral earth pressure coefficient calculated using the equation $K_0 = (1 - \sin \phi') OCR^{\sin \phi'}$ agrees with the K_0 values determined from the experimental data reported by several researchers.
- 15) The number of K_0 studies involving multiple load-unload cycles is limited; no reports of tests with more than 4 cycles were found.

CHAPTER 3

REVIEW OF ANALYTICAL METHODS FOR COMPACTION-INDUCED EARTH PRESSURE

3.1 INTRODUCTION

Experimental studies have indicated that compaction of backfill behind retaining structures can increase earth loads and structural deformations. Prediction of compaction-induced stresses and deflections is difficult because of the many factors involved. Consideration must be given to the interaction between the backfill and the retaining structure, the dimensions, weight, and type of compaction equipment, the dependence of the soil properties on the past and present stress states within the backfill, and the effects of lift thickness and construction procedures. Analytical approaches generally include simplifying assumptions to make the problem more manageable.

Two procedures for the analysis of compaction-induced stresses are reviewed in this chapter: 1) the procedure proposed by Broms (1971) to calculate the after-compaction earth pressures on rigid structures and 2) the procedure presented by Duncan and Seed (1986) for calculation of after-compaction pressures on rigid structures, and its extension to the finite element method by Seed and Duncan (1986) for analysis of stresses and deformations of yielding structures.

3.2 BROMS (1971)

Broms (1971) presented a method for evaluation of earth pressures after compaction. The method was developed for non-yielding vertical retaining structures and is based on the soil model shown in Figure 3.1, which relates the horizontal pressure to the vertical pressure.

The initial stress state for an element of soil is represented by point A in Figure 3.1. The relationship between the horizontal and vertical effective stresses for a compaction cycle is shown by the dashed line for loading from A to C and for unloading from C to E. Broms suggested that this behavior could be approximated as follows: An increase in vertical stress from point A occurs at constant horizontal stress until the K_0 line is intersected at point B, and further increase in the vertical stress is accompanied by an increase in the lateral pressure such that $\sigma_h' = K_0 \sigma_v'$. Unloading from point C on the K_0 line occurs at constant lateral pressure until the K_0' line is intersected at point D, and further unloading is accompanied by a reduction in the lateral pressure such that $\sigma_h' = K_0' \sigma_v'$.

The symbol K_0 is used to represent the lateral earth pressure coefficient during loading. Mayne and Kulhawy (1982) showed that, based on experimental K_0 data, the equation $K_0 = 1 - \sin \phi'$ is reasonably accurate for normally consolidated soils. The value of K_0' corresponds to a passive failure limiting condition on the maximum horizontal stress that can exist for a given vertical stress. Rowe (1954) and Ingold (1979b) suggested the use of the passive earth pressure coefficient for K_0' such that $K_0' = K_p = \tan^2 (45 + \phi'/2)$. Carder, et al. (1977) showed

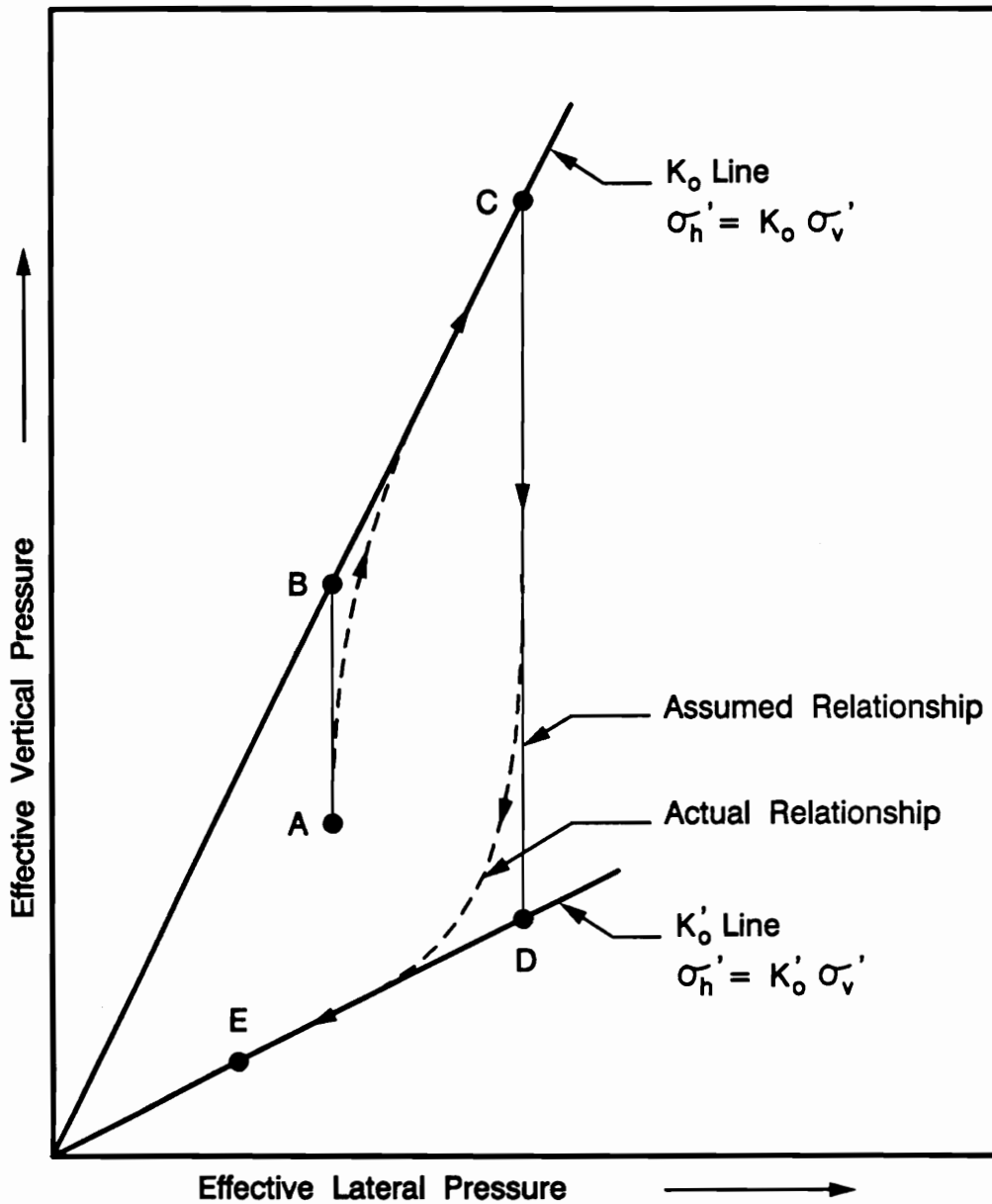


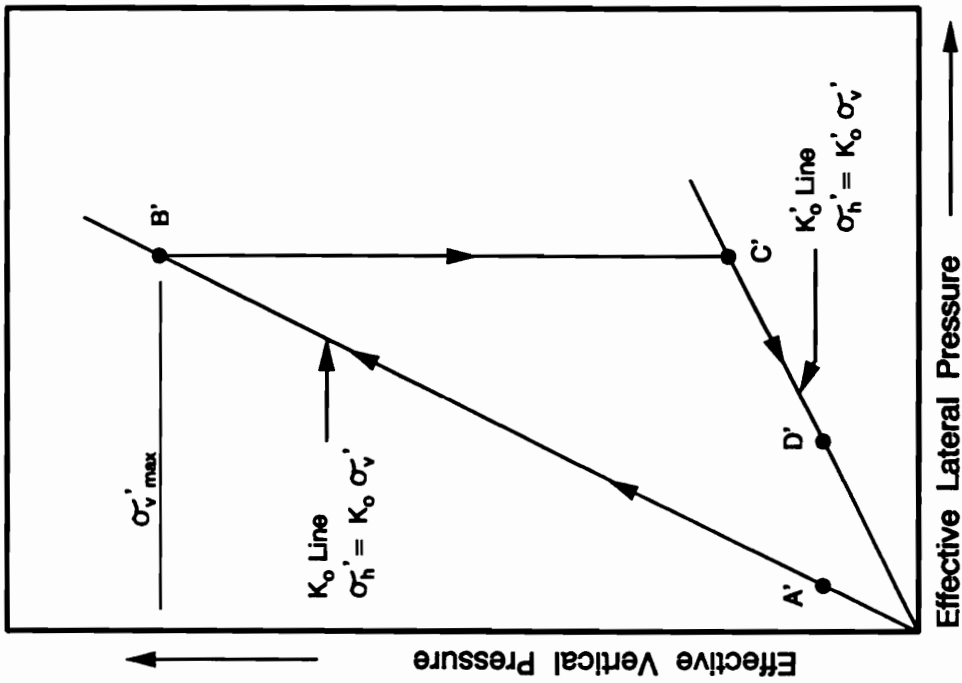
Figure 3.1) Relationships Between Horizontal and Vertical Effective Pressure (after Broms, 1971).

that measured earth pressures after compaction corresponded closely to $K_0' = 1/K_0$ where $K_0 = 1 - \sin \phi'$.

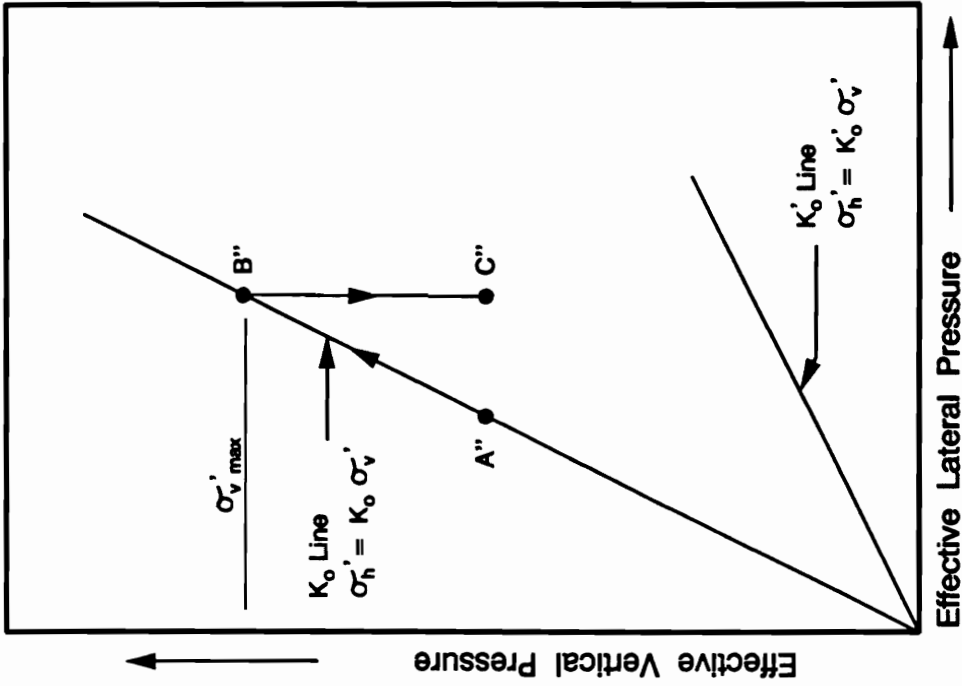
The residual lateral pressure after compaction, at a particular point within the backfill, depends on the depth of the point. If the point is above the critical depth, the stress changes during a compaction cycle are represented by Figure 3.2a where the initial stress is represented by point A', corresponding to the overburden pressure and the at-rest lateral pressure. Compaction causes a large increase in the vertical pressure to $\sigma_{v \max}'$ and a corresponding increase in lateral pressure to $K_0 \sigma_{v \max}'$ (point B'). After compaction, the vertical pressure decreases from B' to C' at constant lateral pressure and from C' to D' along the K_0' line. The final lateral pressure is less than the during-compaction maximum lateral pressure and greater than the initial at-rest pressure. The final vertical pressure is equal to the initial vertical pressure, because compaction does not produce a net increase in vertical pressure.

The stress cycle during compaction for a point located below the critical depth is shown in Figure 3.2b. The initial condition is represented by point A'' on the K_0 line. During compaction, the horizontal and vertical pressures are increased to point B'' on the K_0 line. After compaction, the vertical stress returns to the before-compaction value and the horizontal stress remains at the peak during-compaction value.

Broms suggested that the increase in vertical pressure due to the compaction loading could be calculated using the Boussinesq theory, and



a) depth less than the critical depth



b) depth greater than the critical depth

Figure 3.2) Stress Paths During Compaction (after Broms, 1971).

that the increase in lateral pressure could be calculated as

$\Delta\sigma'_h = K_0 \Delta\sigma'_v$. The peak lateral pressure distribution during compaction of a layer of fill calculated in this way is shown by curve A in Figure 3.3a.

The depth of intersection of curve A with line B is at the critical depth. The lateral pressures after compaction are controlled by line B above the critical depth and by curve A below the critical depth. The critical depth is defined as:

$$z_{cr} = \frac{K_0 \sigma'_{v \max}}{K'_0 \gamma'} \quad \text{Eqn. 3.1}$$

where: z_{cr} = the critical depth,

γ' = the unit weight of the fill above the critical depth,

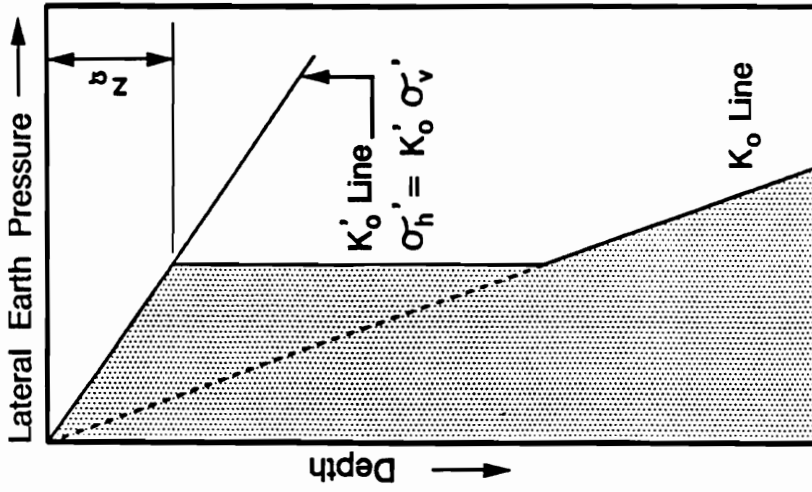
adjusted for buoyancy if the water table is above z_{cr} , and

$K_0, K'_0, \sigma'_{v \max}$ are as defined above.

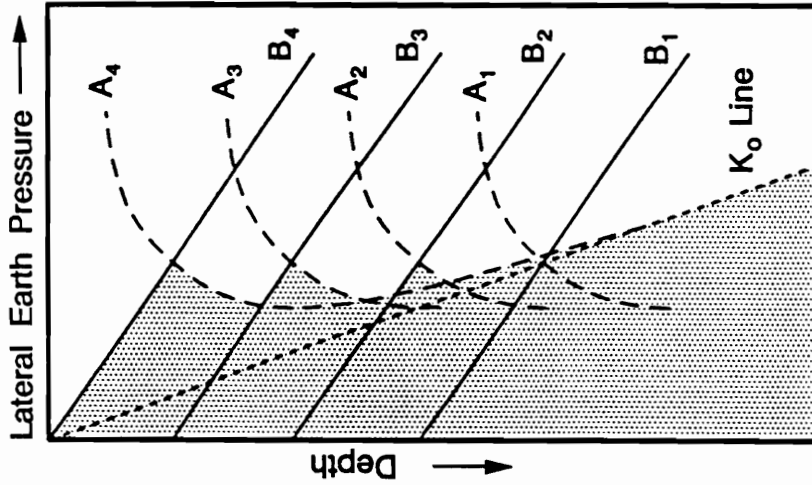
The lateral pressures after compaction for a backfill constructed by compacting several layers of fill can be represented as shown in Figure 3.3b. The shaded area represents the lateral pressure distribution after compaction of the last lift. Broms (1971) suggested that this pressure distribution could be represented by the simplified pressure diagram shown in Figure 3.3c. The simplified diagram is trilinear:

1) Above the critical depth, the lateral pressures are equal to $K'_0 \sigma'_v$

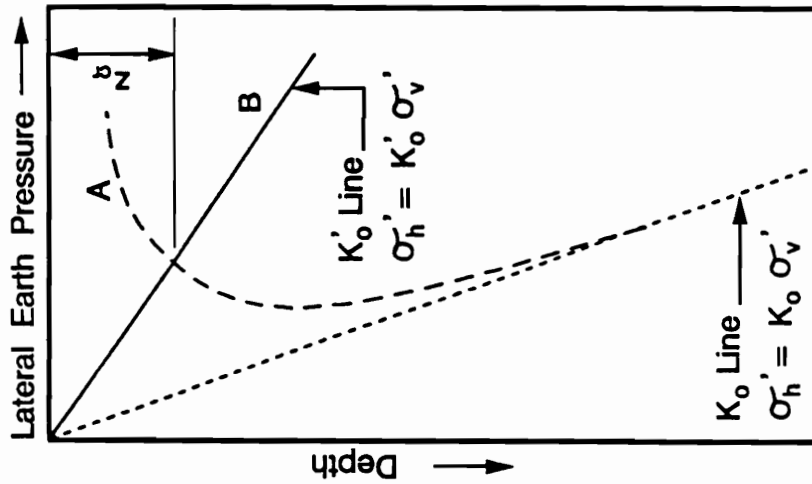
where σ'_v is the effective overburden pressure and K'_0 is the limiting lateral earth pressure coefficient discussed above.



a) single layer



b) multiple layers



c) simplified form for multiple layers

Figure 3.3) Lateral Pressures after Compaction (after Broms, 1971).

- 2) The lateral earth pressure below the critical depth is constant at a value of $K_0' \gamma' z_{cr}$, where K_0' , γ' , and z_{cr} are as defined above, until at some depth this pressure is exceeded by $K_0 \sigma_v'$.
- 3) Below the depth where $K_0 \sigma_v'$ exceeds $K_0' \gamma' z_{cr}$, the lateral pressures are dominated by the effects of the overburden pressure and are represented by $\sigma_h' = K_0 \sigma_v'$.

Broms's method for calculation of the after-compaction lateral earth pressures represents one of the earliest attempts to quantify compaction-induced pressures and provides a logical method of representing the processes of constructing a backfill by compacting a number of lifts. However, the proposed method of calculating the peak lateral stress profile by multiplying the peak vertical stress by a constant factor (K_0) has been found to introduce significant errors in some cases.

Seed and Duncan (1983) noted the importance of calculating $\Delta\sigma_h'$ directly instead of multiplying the calculated value of $\Delta\sigma_v'$ by a constant. Figure 3.4 shows the changes in vertical and horizontal stress, due to a surface applied point load, at four depths, as a function of radial distance from the point load. From inspection of these induced-pressure curves it is clear that the ratio of horizontal to vertical pressure increase is far from constant.

3.3 DUNCAN AND SEED (1986)

Duncan and Seed (1986) developed a method of calculating the compaction-induced lateral pressure based on a multi-cycle

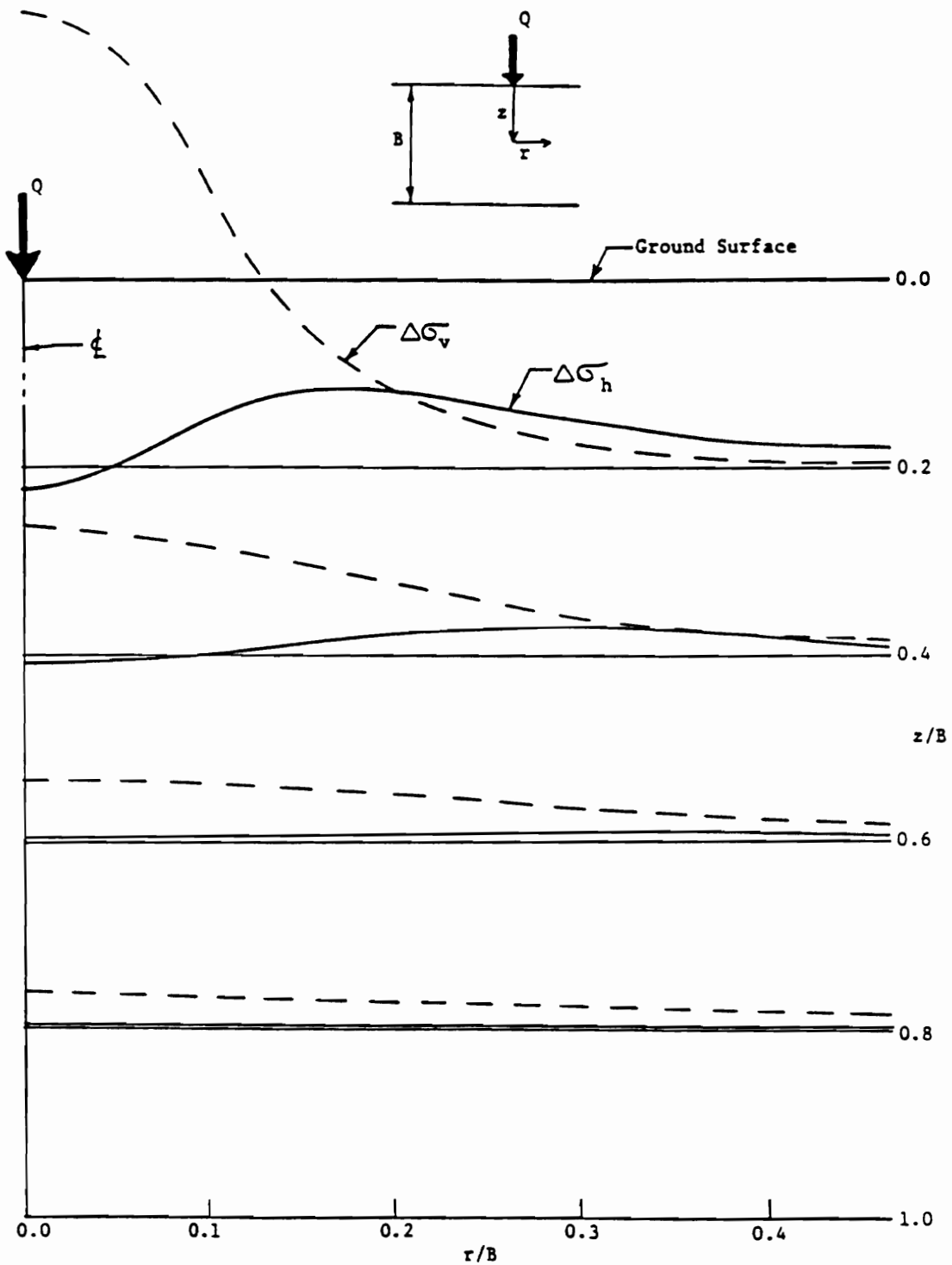


Figure 3.4) Horizontal and Vertical Stresses due to a Surface Applied Point Load (Seed and Duncan, 1983).

K_0 -loading/unloading model. The model and its application to calculating the field compaction-induced stresses are discussed below.

3.3.1 Multi-Cycle K_0 -Loading/Unloading Model

A K_0 -loading/unloading model was developed to represent the lateral pressures on a rigid, frictionless, vertical boundary due to the repeated application and removal of a uniform surcharge load.

Guidelines for evaluation of the parameters used in the model are given in Table 3.1. The model is defined with Figure 3.5, the definition of terms in Table 3.2, and the following principles:

- 1) Initial loading follows the K_0 line such that $\sigma_h' = K_0 \sigma_v'$ where $K_0 = 1 - \sin \phi'$. Virgin loading establishes a new maximum past loading point (MPLP).
- 2) Virgin unloading, defined as the first unloading from a maximum past loading point (MPLP), establishes a new current minimum unloading point (CMUP), and follows the path defined by:

$$\sigma_h' = K_0(\text{OCR})^\alpha \sigma_v' \quad \text{Eqn. 3.2}$$

where: $K_0 = 1 - \sin \phi'$,

OCR = Overconsolidation Ratio,

$$= \frac{\sigma_{v \text{ MPLP}}'}{\sigma_{v \text{ ESS}}'},$$

α = unloading coefficient based on ϕ' and Figure 3.6,

$\sigma_{v \text{ MPLP}}'$ = effective vertical stress corresponding to the Maximum Past Loading Point, and

Table 3.1) Multi-Cycle K_0 -Loading/Unloading Model Parameters (Duncan and Seed, 1986).

Parameter	Name	Recommended Limits	Method of Estimation Based on ϕ'
α	Unloading Coefficient	$0 \leq \alpha \leq 1$	See Figure 3.6 for relationship between α and $\sin\phi'$
β	Reloading Coefficient	$0 \leq \beta \leq 1$	Assume $\beta \approx 0.6$
K_0	Coefficient of At-Rest Lateral Earth Pressure for Virgin Loading	$0 \leq K_0 \leq 1$	$K_0 \approx 1 - \sin\phi'$
$K_{1,\phi'}$	Frictional Component of Limiting Coefficient of At-Rest Lateral Earth Pressure for Unloading	$K_0 \leq K_{1,\phi'} \leq K_p$	$K_{1,\phi'} \approx \tan^2 (45 + \phi'/2)$
c'	Effective Stress Strength Envelope Cohesion Intercept	--	--

Note: K_1 = Limiting Coefficient of At-Rest Lateral Earth Pressure for Unloading.

$$\sigma'_{h,lim} = K_1 \sigma'_v \quad \text{and} \quad K_1 = K_{1,\phi'} + \frac{2c'}{\sigma'_3} \sqrt{K_{1,\phi'}}$$

K_p = Coefficient of Passive Lateral Earth Pressure

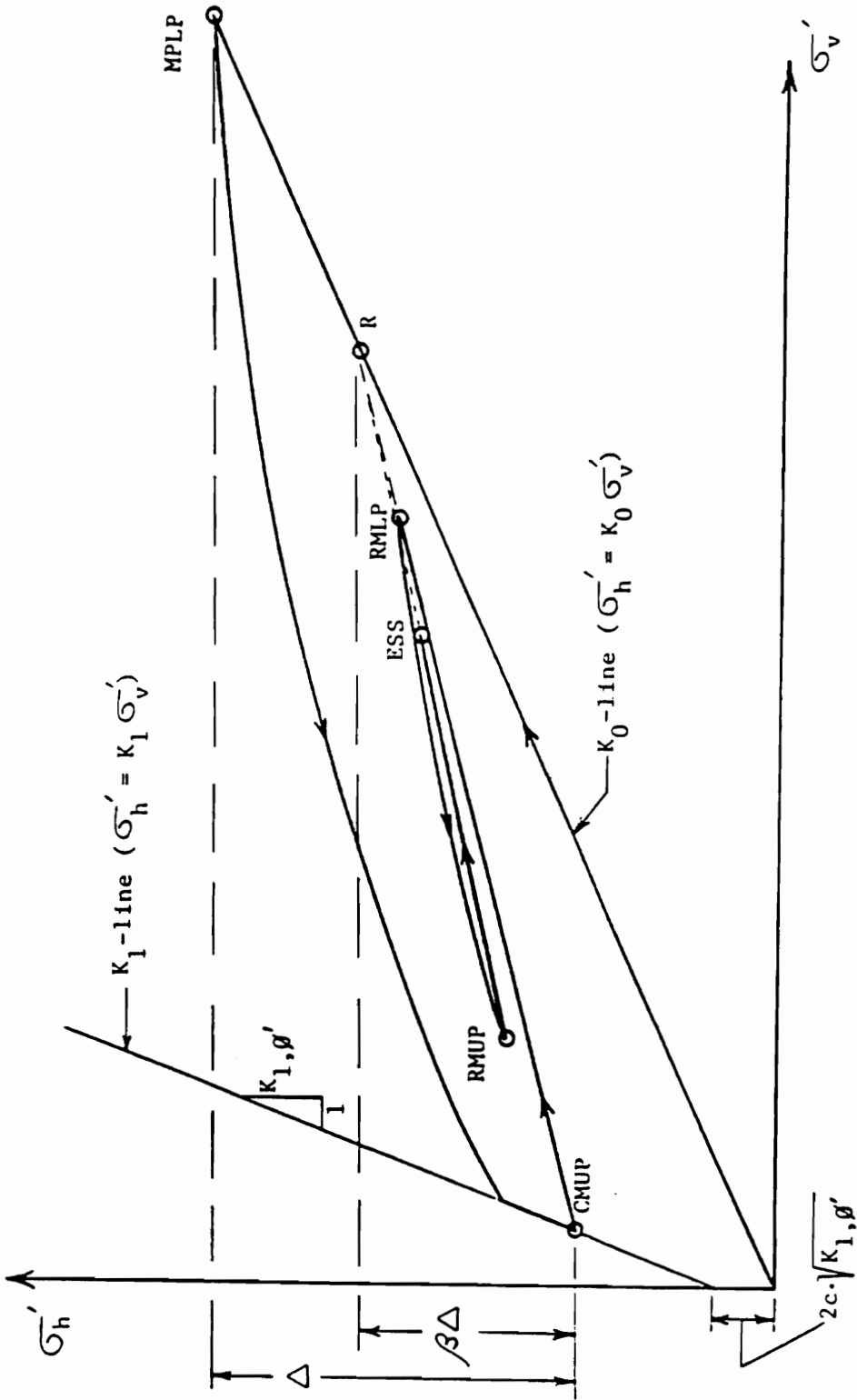


Figure 3.5) Multi-Cycle K_0 -Loading/Unloading Model (Duncan and Seed, 1986).

Table 3.2) Multi-Cycle K_0 -Loading/Unloading Model Definitions (Duncan and Seed, 1986).

Existing Stress State ($\sigma'_{h,ess}$, $\sigma'_{v,ess}$)	The existing lateral and vertical effective stresses
Maximum Past Loading Point ($\sigma'_{h,mplp}$, $\sigma'_{v,mplp}$)	Maximum past lateral and vertical effective stresses
Current Minimum Unloading Point ($\sigma'_{h,cmup}$, $\sigma'_{v,cmup}$)	Lateral and vertical effective stresses at the stress state corresponding to the minimum σ'_h achieved <u>since</u> the MPLP was achieved
Recent Maximum Loading Point ($\sigma'_{h,rmlp}$, $\sigma'_{v,rmlp}$)	Lateral and vertical effective stresses at the stress state corresponding to the maximum σ'_h achieved during the <u>most recent</u> loading cycle.
Recent Minimum Unloading Point ($\sigma'_{h,rmup}$, $\sigma'_{v,rmup}$)	Lateral and vertical effective stresses at the stress state corresponding to the minimum σ'_h achieved during the <u>most recent</u> unloading cycle.
Reloading Point ($\sigma^*_{h,r}$, $\sigma^*_{v,r}$)	Point of intersection between the reloading stress path and the virgin K_0 -line
Δ	Difference in horizontal effective stresses between the MPLP and the CMUP
α^*	Modified or Temporary Unloading Coefficient
β	Fraction of Δ regained in reloading from CMUP to R

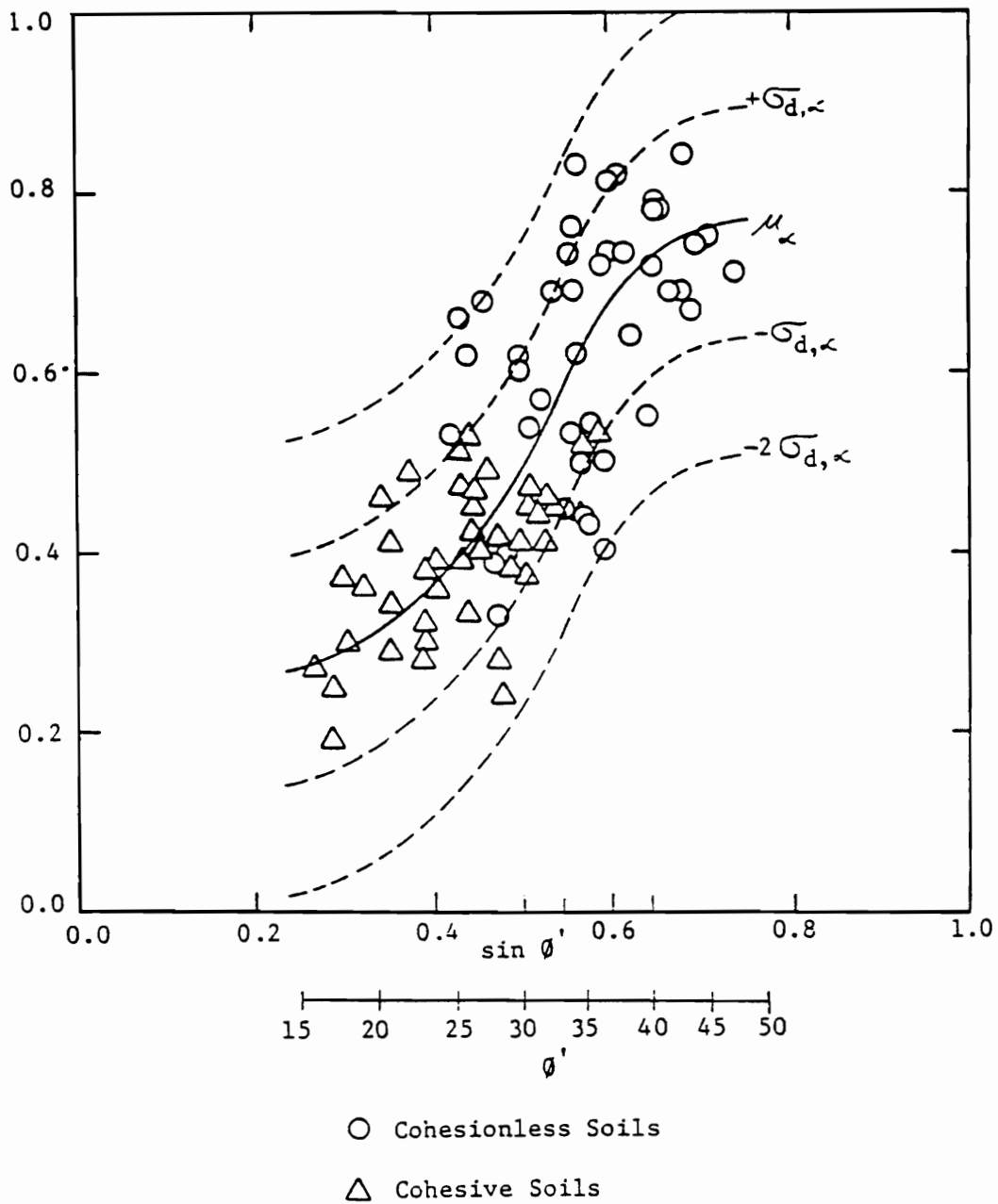


Figure 3.6) Suggested Relationship Between α and $\sin \phi'$ (Duncan and Seed, 1986).

$\sigma'_{v \text{ ESS}}$ = effective vertical stress corresponding to the Existing Stress State.

- 3) The lateral pressure can not exceed $K_1 \sigma'_v$.
- 4) Virgin reloading from the CMUP follows a linear stress path until the virgin loading line is intersected at point R, as shown in Figure 3.5. Point R is located at:

$$\sigma_{h \text{ r}}^* = \sigma'_{h \text{ CMUP}} + \beta \Delta, \text{ and} \quad \text{Eqn 3.3}$$

$$\sigma_{v \text{ r}}^* = (1/K_0) \sigma_{h \text{ r}}^* \quad \text{Eqn 3.4}$$

where: $\Delta = \sigma'_{h \text{ MPLP}} - \sigma'_{h \text{ CMUP}}$.

Reloading to a vertical stress greater than that of the reload point (R) and less than that of the MPLP, takes place along the K_0 line and establishes a new point R. Loading beyond the MPLP establishes a new MPLP and erases the previously established reload point (R). The first unloading from any MPLP constitutes virgin unloading as described by 2) above.

- 5) Nonvirgin unloading from a reload point on the K_0 line follows the stress path defined by:

$$\frac{\sigma'_h}{\sigma'_v} = K_0 \left[\frac{\sigma'_{v \text{ RMLP}}}{\sigma'_{v \text{ ESS}}} \right]^{\alpha^*} \quad \text{Eqn 3.5}$$

where α^* is defined as:

$$\alpha^* = \frac{\ln \left[\frac{\sigma'_{v \text{ RMLP}}}{K_0 \sigma'_{v \text{ CMUP}}} \right]}{\ln \left[\frac{\sigma'_{v \text{ RMLP}}}{\sigma'_{v \text{ CMUP}}} \right]} . \quad \text{Eqn 3.6}$$

If α^* from Equation 3.6 is less than α , then $\alpha^* = \alpha$ and the unloading path is in accordance with Equation 3.5 and establishes a "pseudo CMUP" which performs as a CMUP except that it does not establish a new reload point (R). Any unloading below the true CMUP constitutes virgin unloading as described in 2) and 3) above, and establishes both a new CMUP and a new R.

- 6) Nonvirgin unloading from a point above the K_0 line follows a path shown in Figure 3.7, which is defined by the following procedure:
 - a) The recent maximum loading point (point C) and the CMUP (point B) are projected vertically downward equal distances to C' and B' so that C' is on the K_0 line.
 - b) The unloading path from C' to B' is calculated as described in No. 5 above.
 - c) The actual unloading path is located by projecting the path from C' to B' vertically upward a distance BB' .
- 7) Nonvirgin reloading from the recent minimum unloading point follows a linear stress path to the reload point (R). Reloading beyond the point R and less than the MPLP follows the K_0 line and establishes a new point R. Loading beyond the MPLP establishes a new MPLP and deletes the previously defined point R.

The ability of the model to represent multi-cycle K_0 -loading/unloading was demonstrated by Duncan and Seed (1986) by comparing values

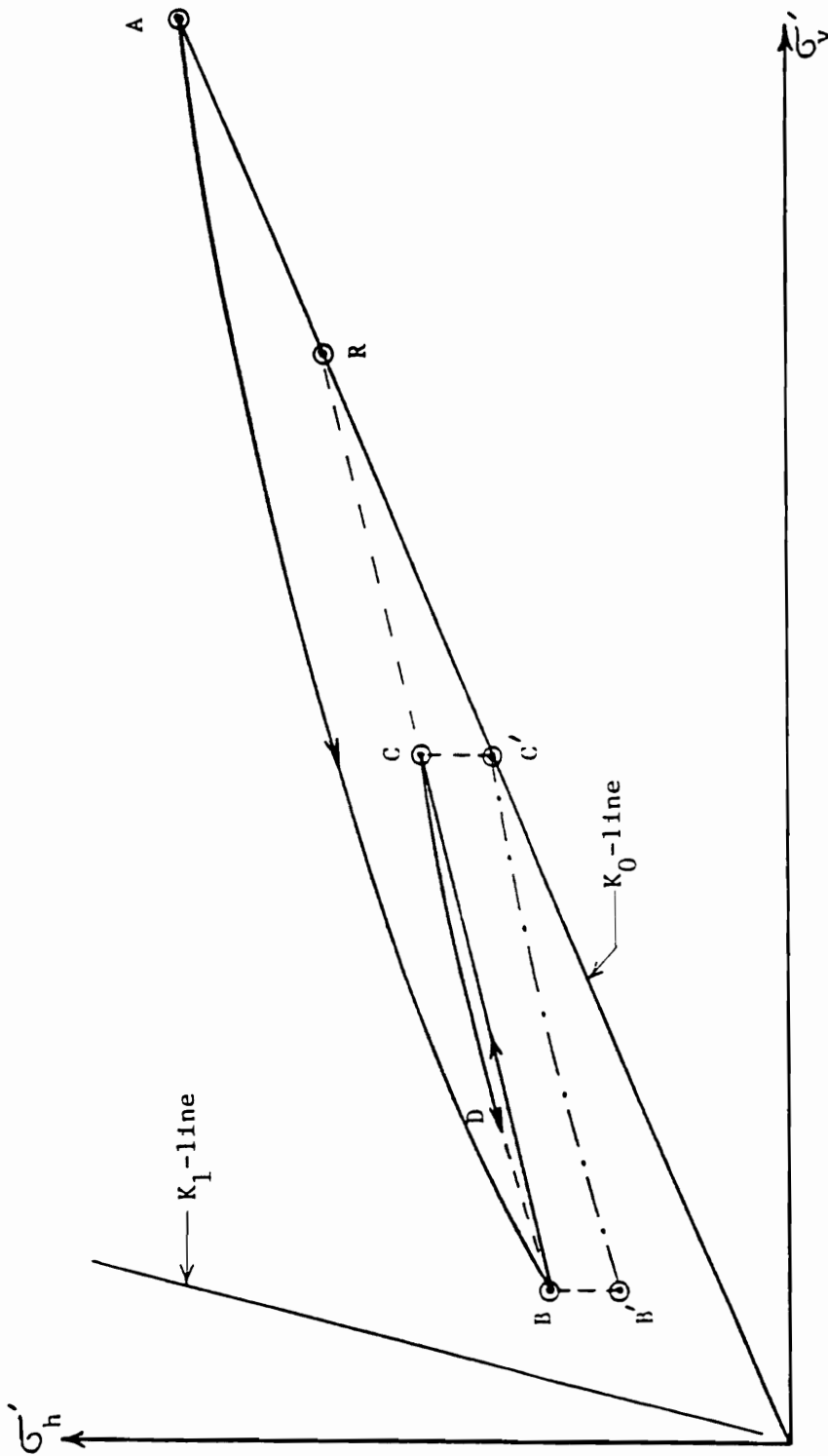


Figure 3.7) K_0 -Unloading Following Partial Reloading (Duncan and Seed, 1986).

of lateral earth pressure calculated using the model to experimental data reported by Wright (1969) and Campanella and Vaid (1972). The difference between the calculated horizontal pressures and the measured values was generally no more than a few percent.

3.3.2 Field Compaction-Induced Stresses

Duncan and Seed (1986) proposed a method for determining the after-compaction lateral earth pressures based on the multi-cycle K_0 -loading/unloading model described in the previous section. Increases in lateral stress due to increasing overburden pressure are modeled directly using the multi-cycle K_0 model. Increases in the lateral stress due to compaction are modeled by determining the peak, virgin, compaction-induced lateral pressure ($\Delta\sigma'_{h\text{ vc p}}$) produced by the most critical positioning of the compaction equipment for a backfill without previous compaction stresses. The equivalent vertical pressure increase ($\Delta\sigma'_{v\text{ e p}}$) that would correspond to the maximum compaction-induced lateral pressure is calculated as

$$(\Delta\sigma'_{v\text{ e p}}) = \frac{\Delta\sigma'_{h\text{ vc p}}}{K_0} \quad \text{Eqn. 3.7}$$

and is used with the K_0 -loading/unloading model to represent compaction by applying and then removing a vertical pressure equal to $\Delta\sigma'_{h\text{ e p}}$.

The peak, virgin, compaction-induced lateral pressures are determined using elastic analysis and the following guidelines given by Duncan and Seed (1986).

1) For the free-field condition, the peak lateral pressure ($\Delta\sigma_{h\text{vc}p}$) due to surface applied compaction loads can be calculated using the Boussinesq elastic solution, with Poisson's ratio equal to

$$v = v_0 + 0.5(0.5 - v_0) \quad \text{Eqn. 3.8}$$

where: $v_0 = \frac{K_0}{1 + K_0}$, and

$$K_0 = 1 - \sin \phi'$$

2) The peak lateral earth pressures at a rigid, vertical, soil-structure interface can be taken as twice the values calculated for the free-field case.

3) The vertical force applied by a vibratory roller can be taken as about two to four times its static weight.

To evaluate the lateral earth pressures of a backfill constructed by placing and compacting horizontal layers of soil, Duncan and Seed (1986) incorporated the multi-cycle K_0 -loading/unloading model into an incremental analytical procedure. The analytical procedure is suitable for evaluating the lateral pressures due to compaction for vertical nondeflecting structures where the backfill is placed and compacted in horizontal layers. The incremental procedure consists of the following steps.

1) The soil parameters for the K_0 -loading/unloading model are evaluated using the guidelines given in Table 3.2,

2) The pressure versus depth profiles for the peak, virgin-compression,

lateral pressure due to the compaction equipment are determined using elastic theory.

- 3) The after-compaction pressures are modeled by an incremental analysis where the horizontal and vertical pressures at the midpoints of each layer are modeled using the K_0 -loading/unloading model. Placement of a new layer of fill produces a permanent increase in the vertical stress of the previously placed layers. Compaction is modeled by a single application and removal of the equivalent vertical stress calculated by Equation 3.7 for the $\Delta\sigma'_{h\text{vc}p}$ corresponding to the depth of the midpoint of the layer. One analysis increment is used to model the placement of a backfill layer and a second is used to model compaction of the layer.

The incremental procedure was coded into the computer program NCOMP (Seed and Duncan, 1983).

A simplified hand-calculation procedure, based on the multi-cycle K_0 -loading/unloading model, was also developed by Duncan and Seed (1986) for cases where the same profile of $\Delta\sigma'_{h\text{vc}p}$ can be used for all layers of the backfill. For these cases, the simplified solution and the incremental solution produced values that were similar for a number of conditions.

Seed and Duncan (1986) incorporated a form of the K_0 -loading/unloading model into a finite element program for the analysis of stresses and deformations for problems that involve yielding structures, sloping backfills, or irregular backfill or structure geometry.

CHAPTER 4

INSTRUMENTED OEDOMETER

4.1 INTRODUCTION

The at-rest lateral earth pressure coefficient K_0 (the ratio of horizontal pressure to vertical pressure under the condition of zero lateral strain) is an important parameter in the models used to evaluate compaction-induced earth pressures. It is generally recognized that the at-rest lateral earth pressure coefficient is dependent on soil type, density, and stress levels (Kjellman, 1936; Bishop and Henkel, 1957; Bishop, 1958; Brooker and Ireland, 1965; Wright, 1969; Broms, 1971; Mayne and Kulhawy, 1982; Ofer, 1981; Duncan and Seed, 1986; and Seed and Duncan, 1986).

Although field compaction of soil by vibratory compaction equipment may involve tens or hundreds of loading cycles, data regarding values of K_0 are only available for tests with four or fewer loading cycles. It is therefore of considerable importance to investigate the effects of large numbers of load cycles on the value of K_0 , to determine values appropriate for estimating earth pressures due to vibratory compaction. An instrumented oedometer has been developed as part of this study to investigate the effect of large numbers of load cycles on the value of K_0 . The instrumented oedometer is interfaced with a microcomputer based data-acquisition and control system. With this arrangement, one pressure increment and data recording requires about 6 seconds. At this

rate, a test involving 1000 load cycles can be completed in about 3.5 hours.

The following sections describe the instrumented oedometer and its support equipment, preliminary studies with the instrumented oedometer, and the current investigation of the effects of large numbers of load cycles on the value of K_0 for Monterey #0/30 sand.

4.2 INSTRUMENTED OEDOMETER

The instrumented oedometer developed during this study uses a 6-inch diameter by 1-inch high specimen. The oedometer is split into two halves along a diameter and the two halves are held together by two load cells, as shown in Figures 4.1 and 4.2. The load cells are used to measure the force exerted on the inside of the oedometer by the horizontal earth pressure. For the purpose of the following discussion, it is convenient to identify the two halves of the split oedometer as a fixed half and an instrumented half, as shown in Figures 4.1 and 4.2.

The base and the cap are both attached to the fixed half of the oedometer. The base is attached to the bottom side of the fixed half using four bolts. One 0.005 inch thick shim washer is used at each bolt location to maintain a small gap between the oedometer and the base. The gap between the base and the instrumented half is maintained by a hardened steel ball between two hardened steel inserts. Maintaining the gap insures zero lateral force transfer between the base and the instrumented half of the oedometer.

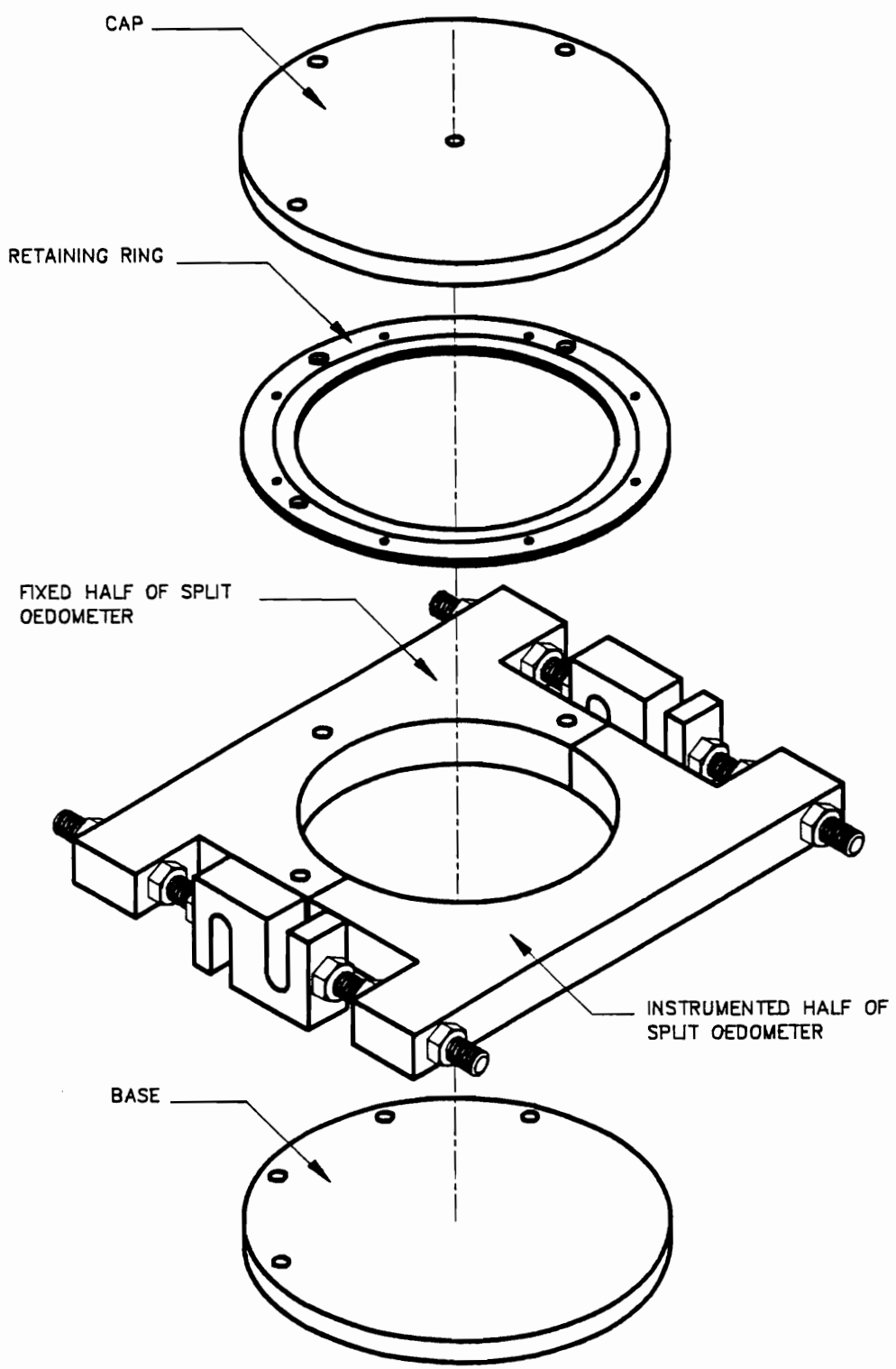


Figure 4.1) Main Components of the Instrumented Oedometer.

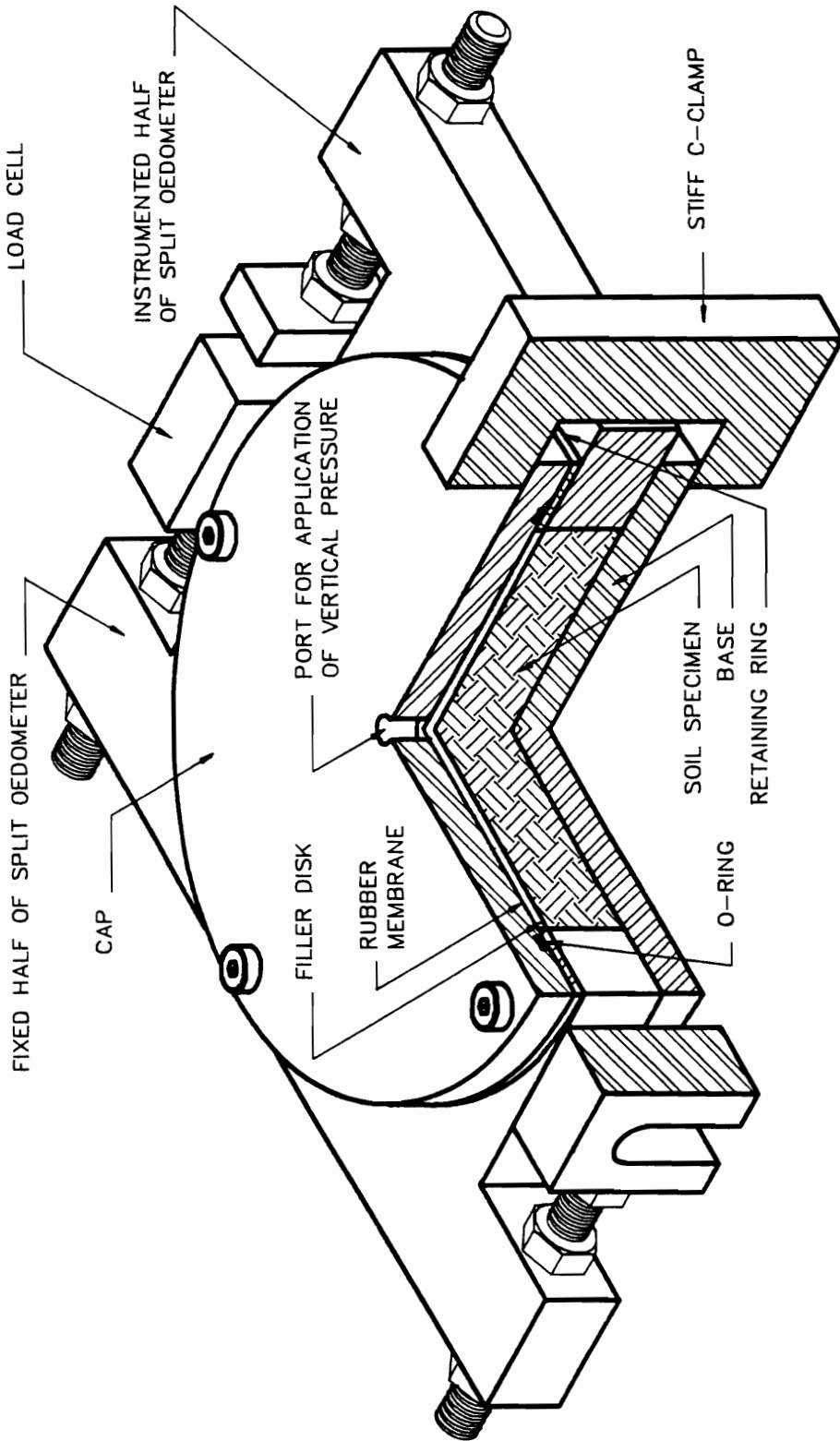


Figure 4.2) Instrumented Oedometer.

The cap assembly consists of the cap, an O-ring, a rubber membrane, and a retaining ring. The O-ring and retaining ring are used to clamp the rubber membrane to the bottom side of the cap. During a test, vertical pressure is applied to the specimen by pressurizing the rubber membrane through a port in the center of the cap. The cap assembly is attached to the fixed half of the split oedometer using three bolts. Shim washers are used at the bolt locations to maintain a gap between the cap assembly and two halves of the oedometer.

During assembly of the oedometer, the mounting bolts supporting the load cells are adjusted to provide a 0.002-inch to 0.004-inch gap between the two halves of the instrumented oedometer. With this arrangement, the only horizontal forces acting on the instrumented half of the oedometer are those due to the lateral pressure of the soil inside the oedometer, and the restraint of the load cells.

Preliminary studies by Knight (1988) using the instrumented oedometer revealed that during the application of vertical pressure to the specimen, the deflection of the cap and base influenced the test results. To correct this problem, a very stiff fixed-dimension C-clamp was devised to restrain the deflection of the cap and the base. The fixed-dimension C-clamp insures that the gap between the cap and the instrumented half of the oedometer is maintained at 0.002 inch to 0.005 inch during testing.

Samad (1988) and Knight (1988) found that the accuracy and repeatability of the test results increased when a filler disk was used between the top of the specimen and the rubber membrane through which

the loads are applied. The use of a filler disk allows pressure to be applied to the specimen with only a small movement of the membrane. The filler disk was constructed by forming a one-eighth-inch-thick flexible rubber sheet inside a Plexiglas® ring, also one-eighth inch thick. The inside diameter of the Plexiglas® ring is 5.5 inches and the outside diameter is about 5.95 inches. The filler disk is centered on top of the specimen by four locating pins in the top of the oedometer.

A microcomputer-based data-acquisition and control system controls the vertical pressure and records the load cell and pressure transducer readings.

4.3 SIGNAL CONDITIONING AND DATA ACQUISITION

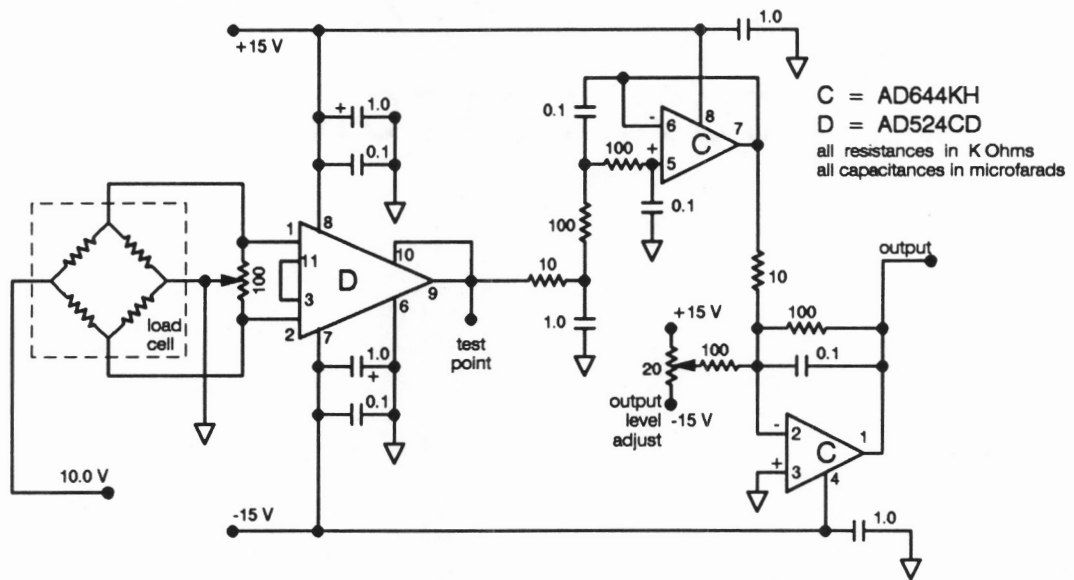
The output signals of the two load cells and the pressure transducer are recorded by a microcomputer-based data-acquisition system after being amplified and filtered by a custom signal-conditioning unit. The analog outputs of the signal-conditioning unit are converted to digital form by a MetraByte DAS-8 expansion card in the microcomputer. The resolution provided by the 12 bit conversion process of the DAS-8 is about 2.4 millivolts.

The lateral stiffness of the instrumented oedometer is controlled by the stiffness of the load cells. Commercially available load cells with maximum capacity of 1000 pounds were determined to be stiff enough to limit the lateral deformation of the oedometer to less than 0.001 of an inch for the expected range of lateral pressures. However, connecting the load cells directly to the DAS-8 was not practical because the

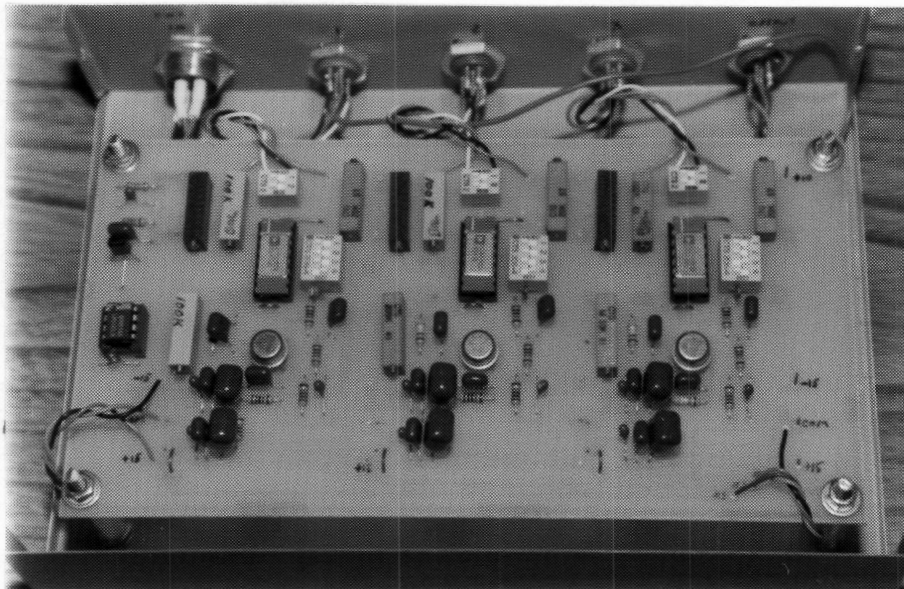
maximum expected forces would produce an output signal of only about two millivolts, about the same value as the resolution ability of the DAS-8. A custom high-gain amplification and filtering circuit was designed to increase the signal level by a factor of about 5000 and improve the signal-to-noise ratio.

A three-channel signal-conditioning unit with a 10-VDC voltage supply for transducer excitation was fabricated based on the single-channel schematic shown in Figure 4.3a (Chan, 1988). The unit, shown in Figure 4.3b, provides variable amplification, offset adjustment, and low-pass filtering for each of the three analog data channels. The excitation and signal leads from the load cells and the pressure transducer are connected to the signal-conditioning unit and the outputs from the amplifier circuits are connected to the DAS-8 analog-to-digital conversion board in the microcomputer. During calibration, each amplification circuit is adjusted to maximize the sensitivity of the instrumentation system.

With this signal-conditioning and data-acquisition system the lateral forces can be measured with an accuracy of about ± 0.05 pounds, corresponding to accuracy of the calculated lateral earth pressure of about ± 0.02 lbs/in². The vertical pressure is determined by using an electrical pressure transducer to measure the air pressure applied to the rubber membrane. The accuracy of the vertical pressure measurement is about ± 0.05 lbs/in². The accuracy with which K_0 can be calculated is a function of the pressure and K_0 , as indicated in Figure 4.4. At



a) schematic of a single-channel analog amplification and filtering circuit (Chan, 1988)



b) three-channel analog signal-conditioning unit

Figure 4.3) Analog Signal Conditioning Equipment.

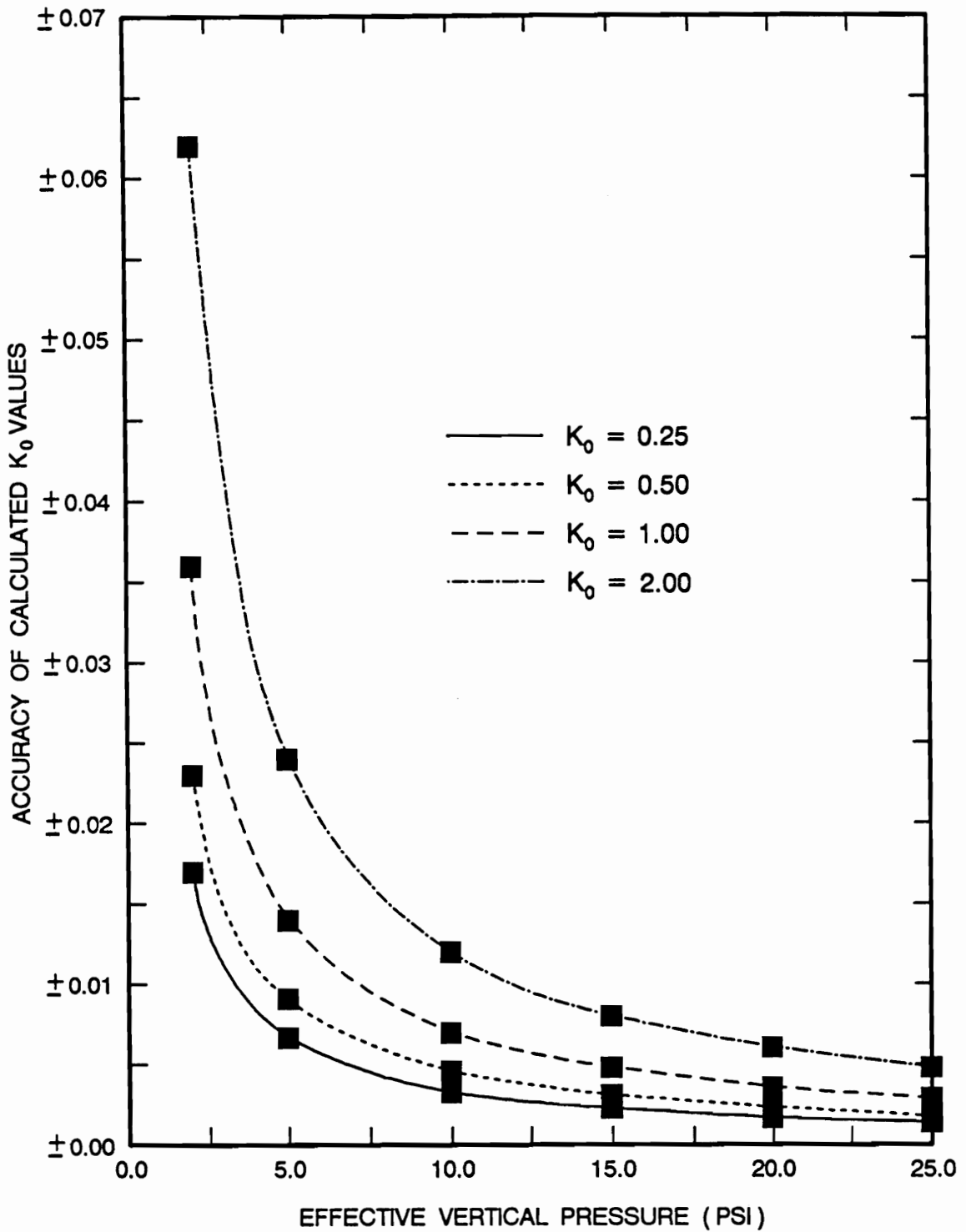


Figure 4.4) Relationship Between the Accuracy of the Calculated Values of K_0 and the Effective Vertical Pressure for Several Values of K_0 .

vertical pressures greater than 5 lbs/in² the accuracy of K_0 is ± 0.015 or better for K_0 values less than 1.0.

4.4 TEST CONTROL

The operation of the instrumented oedometer is controlled by a microcomputer-based system consisting of a microcomputer, a digital pressure regulator, a custom digital interface, and a control program. The system components are shown in Figure 4.5.

The test control program is coded in Microsoft QuickBASIC 4.5. Appendix A contains a listing of the control program. The interactive program guides the operator through the initial stages of adjusting the supply pressure regulator and recording the initial transducer readings. The operator defines the loading sequence for the test by responding to a series of prompts. After the load sequence has been entered and the operator has given the instruction to begin the test, all procedures are under computer control. For each pressure increment, the horizontal and vertical pressures and the calculated value of K_0 are written to a data file. During the test, the transducers are sampled several times per second and the display is updated to provide a continuous readout of the horizontal and vertical pressures and the value of K_0 .

The vertical pressure is controlled by a Schrader PAR-15 digital pressure regulator. The output pressure of the PAR-15 depends on the pressure supplied to its inlet port and the four bit digital input signal. Sixteen different pressures are available ranging from zero (atmospheric pressure) to the full pressure supplied to the PAR-15 inlet

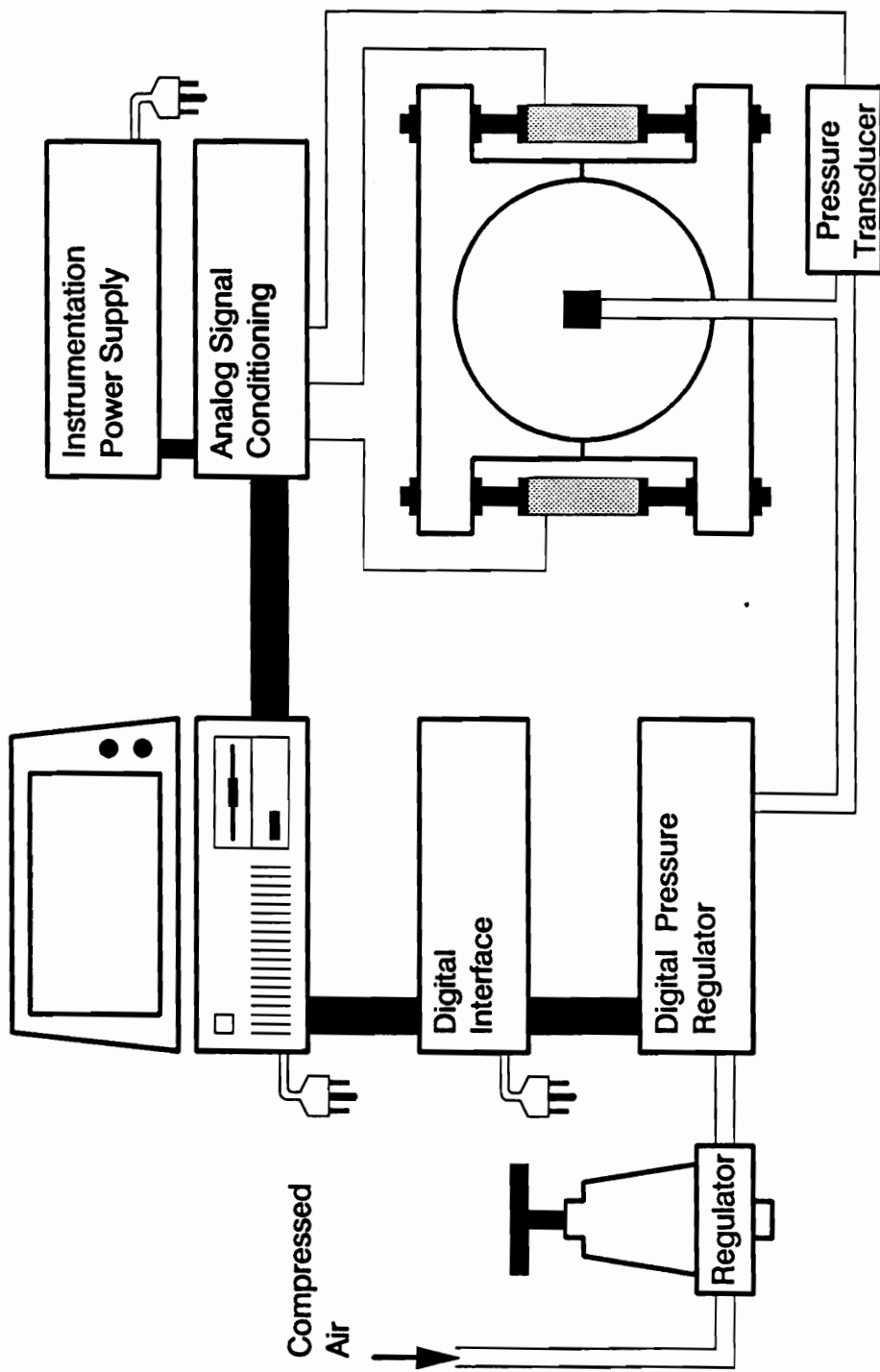


Figure 4.5) Instrumented Oedometer and Data Acquisition/Control System.

port in increments of 1/15 times the supply pressure. The digital pressure regulator is controlled by the test control program via the computer's parallel communications port and a digital interface unit. The interface unit is required because the signal from the parallel port is +5 VDC and the PAR 15 requires a 120 VAC input signal.

Once started, the test continues with minimal interaction from the operator. Before writing a data value to the file, the program checks the value to make sure it does not correspond to the extreme upper or lower limit of the input range of the DAS-8. A value equal to one of these extremes generally indicates that the analog signal is beyond the input limits of the DAS-8. If an out-of-range value is detected, the program suspends the test sequence until the operator gives the instruction to continue.

4.5 DESCRIPTION OF MONTEREY SAND

Monterey sand #0/30 is a commercially available clean uniform sand. The sand is primarily quartz with some feldspar and the grains are sub-angular to sub-rounded. Figure 4.6 shows the grain size distribution reported by Milstone (1985) for a sample taken from the same shipment of sand used for the K_0 tests. Table 4.1 lists the index properties for the Monterey sands tested by Milstone (1985) and Muzzy (1983). Based on the similarity of the grain size and the fact that both samples were Monterey #0/30 sand, it seems reasonable to adopt the maximum and minimum void ratios reported by Muzzy (1983) as representative of the sand used for this study.

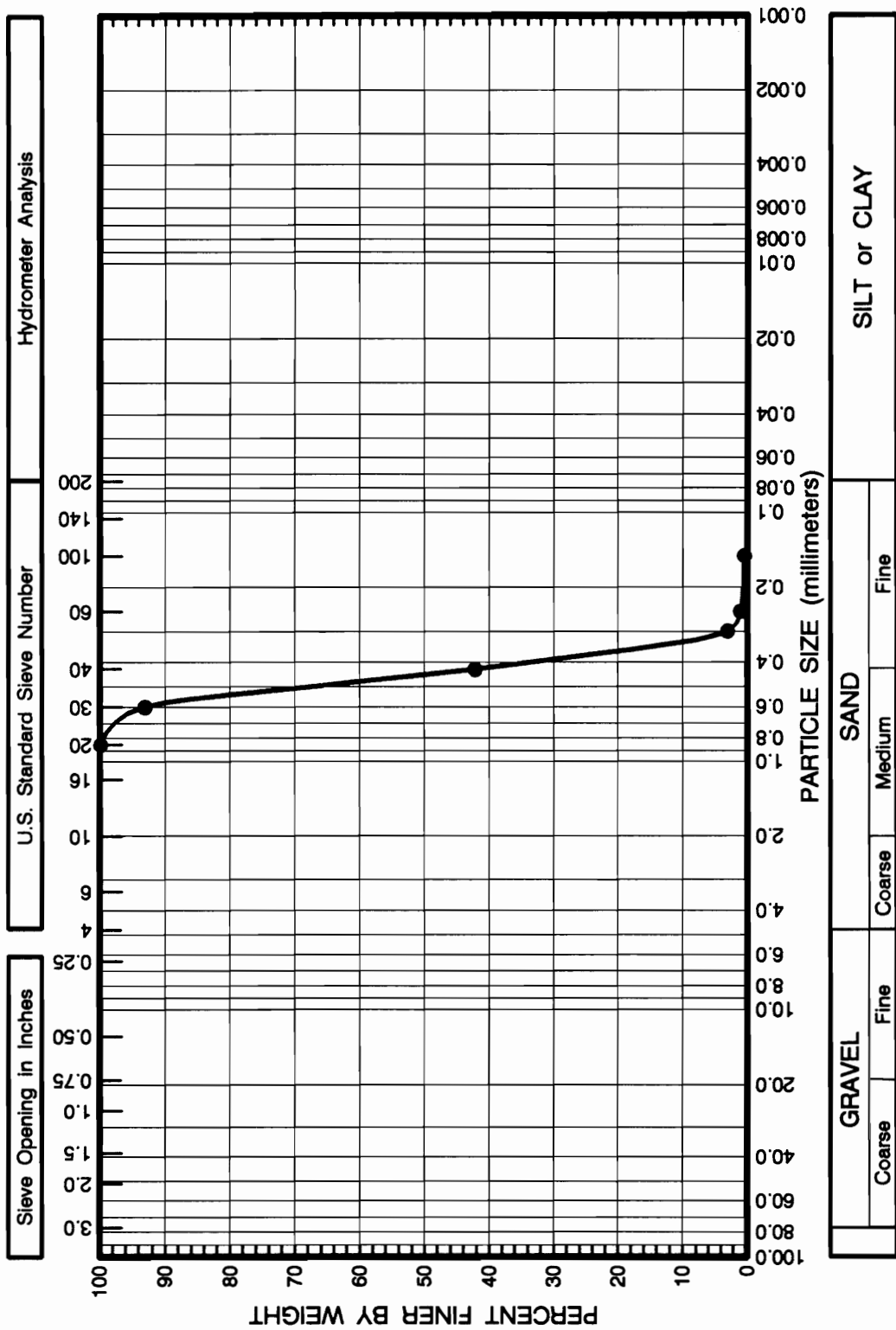


Figure 4.6) Grain Size Distribution of Monterey #0/30 Sand (Milstone, 1985).

Table 4.1) Index Properties for Monterey #0/30 Sand (Milstone, 1985).

	Muzzy (1983)	Milestone (1985)
G_s	2.65	2.65
$\gamma_d \text{ max}$	105.8 lbs/ft ³	---
$\gamma_d \text{ min}$	91.7 lbs/ft ³	---
e_{max}	0.803	---
e_{min}	0.563	---
D_{50}	0.45	0.45
C_u	1.60	1.37
C_c	1.00	0.95

4.6 PRELIMINARY STUDIES

The first two studies using the instrumented oedometer (Samad, 1988; and Knight, 1988) concentrated on evaluating the performance of the K_0 device for static loading, and making modifications to improve the accuracy and repeatability of the test results. The instrumented oedometer used by Samad (1988) and Knight (1988) was the same one used in the current studies. Improvements were made during each of the studies, and the data-acquisition system was developed after the studies of Samad (1988) and Knight (1988) were completed. During the earlier studies, the pressures were controlled either by adjusting the signal voltage to an electropneumatic pressure regulator (Samad, 1988) or by manually adjusting a pressure regulator. The outputs of the load cells and the pressure transducers were monitored using digital voltmeters and were recorded by hand.

The studies by Samad (1988) and Knight (1988) produced a number of findings relating to the use of the instrumented oedometer to investigate K_0 and resulted in several changes to the instrumented oedometer. The primary findings and changes were:

- 1) To produce consistent results, it was important to assemble the equipment in exactly the same manner for each test.
- 2) Use of a filler disk at the top of the specimen increased the accuracy of the test results. The one-eighth-inch-thick filler disk with a narrow outer band of Plexiglas® and center of flexible rubber was developed for this purpose.

- 3) The test results were influenced by deformations of the cap and base in response to the vertical pressure. The use of a very stiff C-clamp across the free edges of the cap and base essentially eliminated these deformations and improved the quality of the test results.
- 4) A specimen of flexible rubber, formed to the exact dimensions of the oedometer, was useful for evaluating the performance of the instrumented oedometer because its Poisson's ratio is very near 0.5 and therefore the value of K_0 is very near unity. Furthermore, the rubber is elastic and its lateral pressure coefficient is independent of stress history and number of load cycles. These properties of the rubber specimen make it very useful for calibration tests.
- 5) Based on data from tests using the instrumented oedometer with the improvements suggested by these two studies, values of K_0 were determined for Monterey #0/30 sand. The measured values were found to be reasonable and to agree with data reported by Wright (1969) and Knight (1988).
- 6) An automated test control and data-acquisition system is needed to perform tests with large numbers of load cycles.

4.7 CURRENT STUDIES

The current studies using the instrumented oedometer focused on developing and testing an automated test control and data-acquisition system and investigating the influence of large numbers of load cycles on the value of K_0 for Monterey sand #0/30.

The automated test control and data-acquisition system was evaluated by performing tests on a specimen constructed of flexible silicone rubber. Figure 4.7 shows the results of a test using the rubber specimen. The solid line represent the data recorded for the first and last (18th) load/unload cycles and the dashed line represents a slope with $K_0 = 0.98$. The measured value of $K_0 = 0.98$ is slightly lower than the theoretical value of 1.0 for an incompressible material with Poisson's ratio equal to 0.5. The difference is believed to be due to a small volume of air within the silicone rubber that could not be removed during the fabrication process. The entrapped air would reduce Poisson's ratio to a value slightly less than 0.5, and the corresponding lateral pressure coefficient would be slightly less than unity. The linearity of the relationship between the lateral and vertical pressures and the similarity between the first and last load/unload cycles indicated that the instrumented oedometer and the automated test control and data-acquisition system were functioning correctly.

4.7.1 Test Procedure

Test specimens were formed by pouring sand from a stoppered bottle through a small diameter tube into the oedometer. This technique enabled specimens of different densities to be formed by adjusting the diameter of the tubing and the distance between the tubing and the surface of the specimen. The specimen for test number 7 was vibrated to increase its density after deposition.

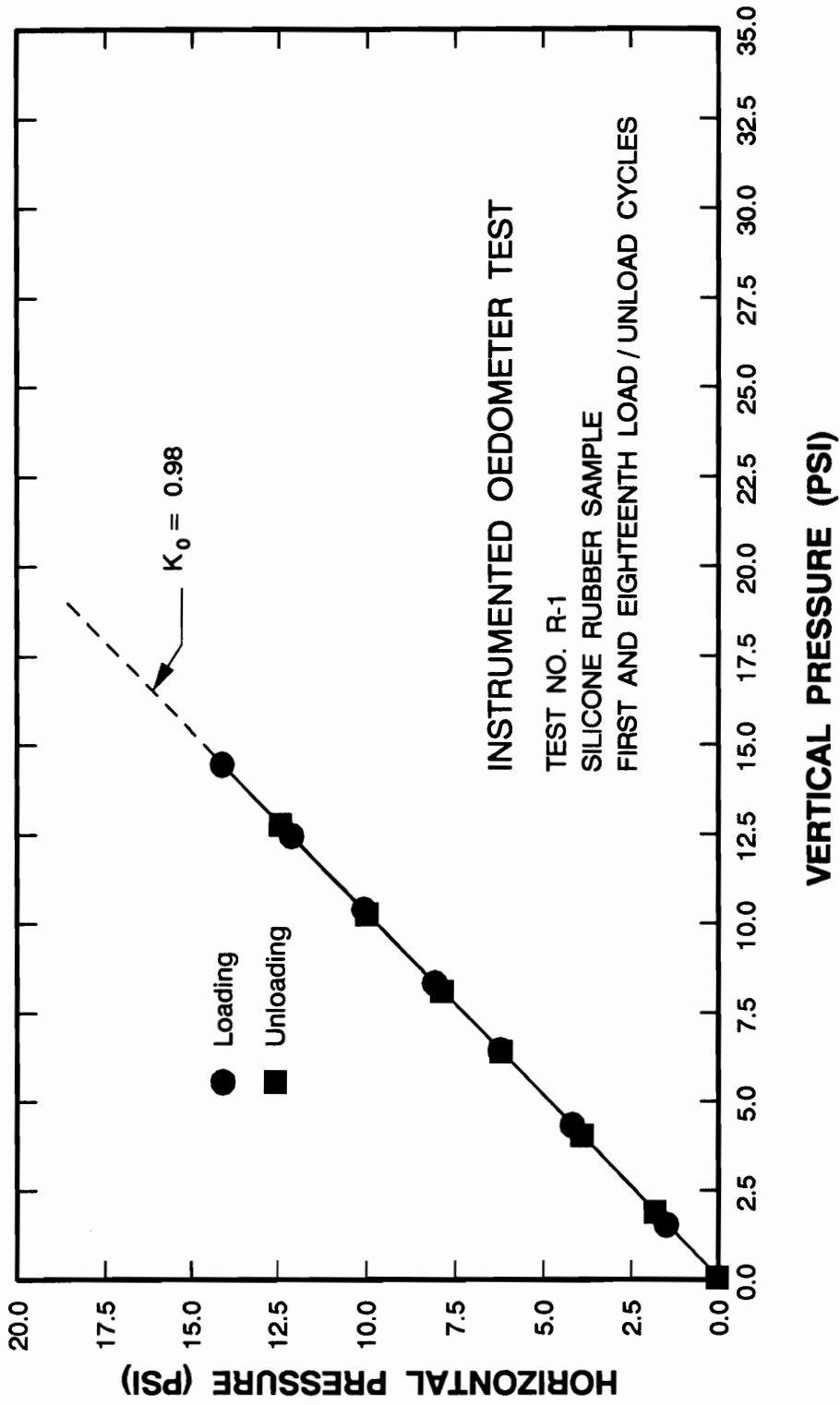


Figure 4.7) Results of an Instrumented Oedometer Test Using a Silicone Rubber Specimen.

Each specimen was subjected to 1000 cycles of vertical loading. Two types of load cycles were used: fast cycles, starting at a low pressure, increasing to the peak pressure with one pressure increment, and returning to a low pressure with a second increment; and slow cycles, starting at a low pressure, increasing to the peak pressure with increments of about 1/15 of the peak pressure, and returning to a low pressure with the same increments. The patterns used for the five tests during this study were similar:

- 1) 1st cycle - one slow cycle, loading from zero pressure to the maximum pressure and unloading to zero pressure,
- 2) 2nd cycle - one slow cycle, loading from zero pressure to the maximum pressure and unloading to an intermediate pressure,
- 3) 3rd, 10th, and 100th cycles - one slow load/unload cycle between the intermediate and the maximum pressures,
- 4) 4th through 9th, 11th through 99th, and 101st through 999th cycles - fast load/unload cycles between the intermediate and maximum pressures,
- 5) 1000th cycle - one slow cycle, loading from the intermediate pressure to the maximum pressure and unloading to zero pressure.

The peak vertical pressure for all of the tests was about 30 lb/in². The intermediate pressure for each test is given in Table 4.2 along with specimen density information. The effective friction angles listed in Table 4.2 are based on the empirical relationship: $\text{Constant} = e \tan \phi'$. The constant for Monterey #0/30 sand was determined to be about 0.56 by Knight (1988).

Table 4.2) Summary of Instrumented Oedometer Tests.

Test Number	Approximate Intermediate Pressure (lb/in ²)	Dry Density (lb/ft ³)	Void Ratio	Relative Density ¹ (%)	Effective Friction Angle ²
3	6.5	101.8	0.625	74	42
4	2.0	102.7	0.611	81	42
5	14.5	102.2	0.619	77	42
6	6.5	91.6	0.806	0	35
7	6.5	103.5	0.598	85	43

¹ Relative densities are based on $e_{min} = 0.563$ and $e_{max} = 0.803$.

² Effective friction angles are based on the empirical relationship $0.56 = e \tan \phi'$.

4.7.2 Test Results and Discussion

During each test, the load cell and pressure transducer readings were recorded for each applied pressure value. The data for the 1st, 2nd, 3rd, 10th, 100th and 1000th load cycles of tests 3 through 7 are shown in Figures 4.8 through 4.12.

With the exception of test number 6, the initial relative densities of the specimens ranged from 74 percent to 85 percent. This range in relative density corresponds to a range in the dry density from 101.8 lb/ft³ to 103.5 lb/ft³. Based on the empirical relationship $0.56 = e \tan \phi'$, the effective friction angles for these specimens are estimated to be between 41.9° and 43.1°. The narrow range of effective friction angle values suggests that these samples should exhibit similar behavior under K_0 loading conditions. Tests number 3 through 5 and number 7 will be discussed as a group, and test number 6 will be discussed subsequently.

The values of K_0 observed during first loading were: 0.42 for tests number 4 and 5, 0.44 for test number 3, and 0.37 for test number 7. The lowest value of K_0 was recorded for test number 7. Test number 7 had the highest density and would therefore be expected to have the lowest value of K_0 . The relatively large difference between the K_0 value of 0.37 for test number 7 and the average value of $K_0 = 0.43$ for the remaining three tests of this group may be due to a difference in the specimen preparation procedure. The specimens for tests 3 through 5 were formed by pouring sand into the oedometer as described earlier.

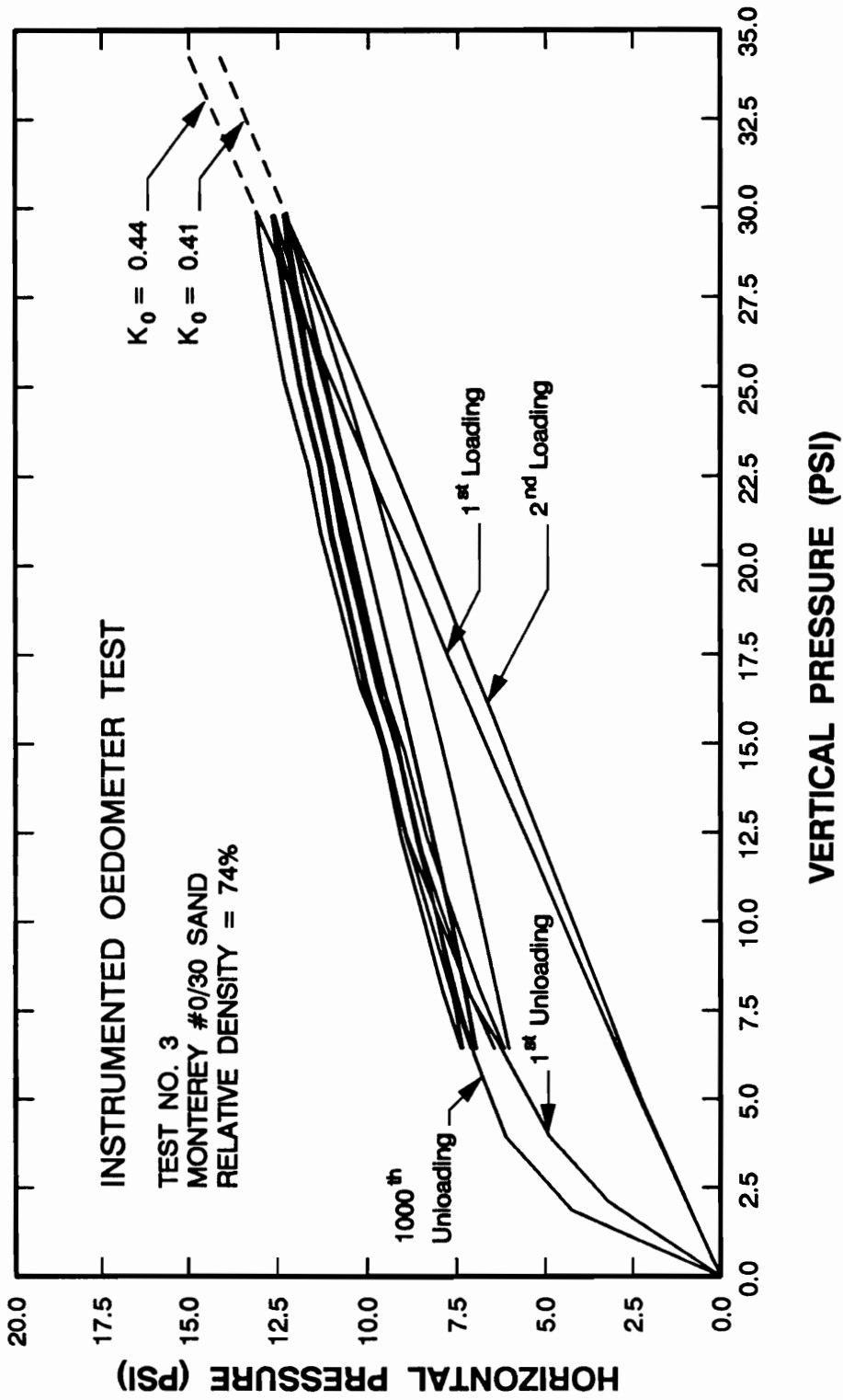


Figure 4.8) Results of a Multicycle K_0 Test on Monterey #0/30 Sand, Test Number 3.

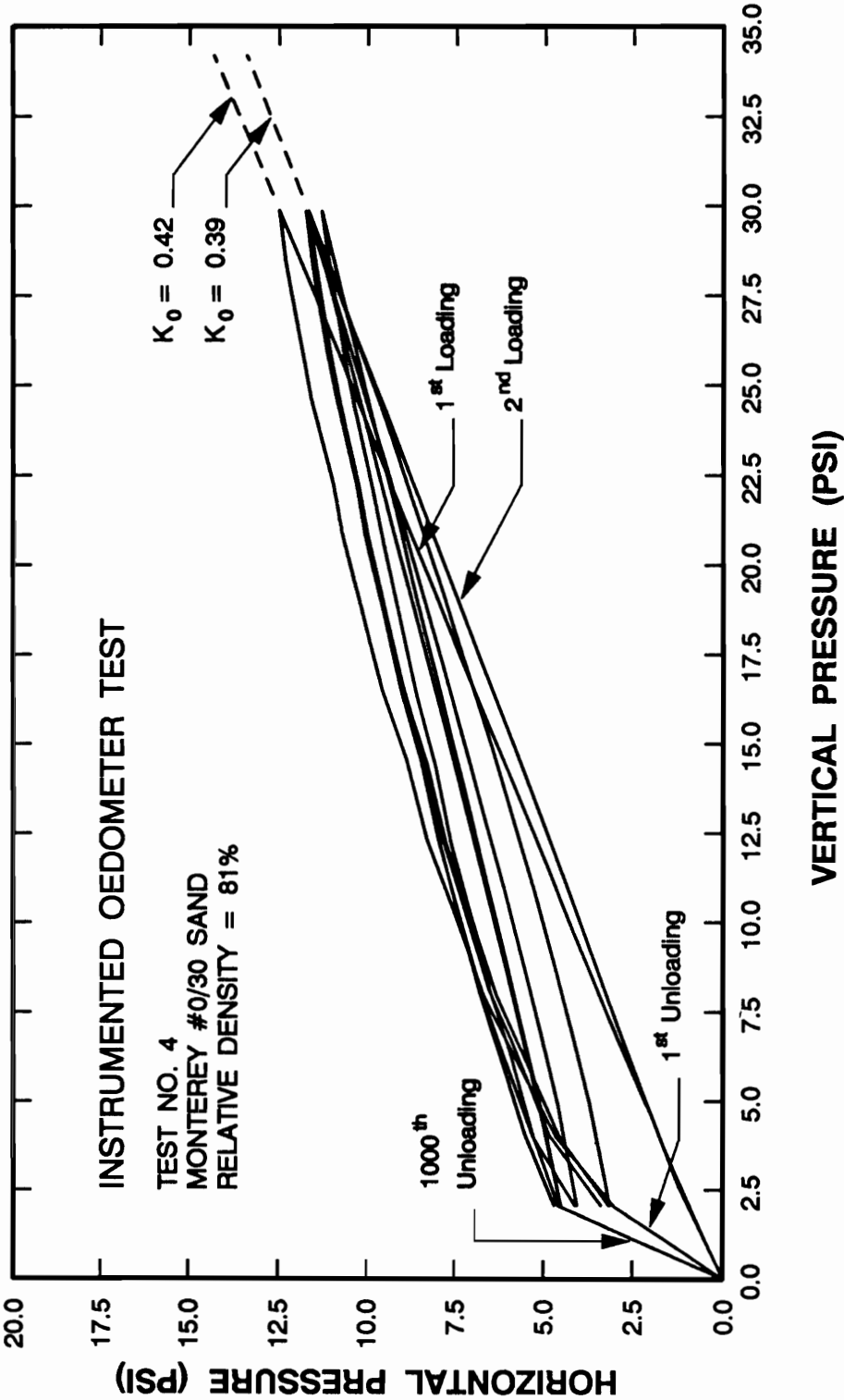


Figure 4.9) Results of a Multicycle K_0 Test on Monterey #0/30 Sand, Test Number 4.

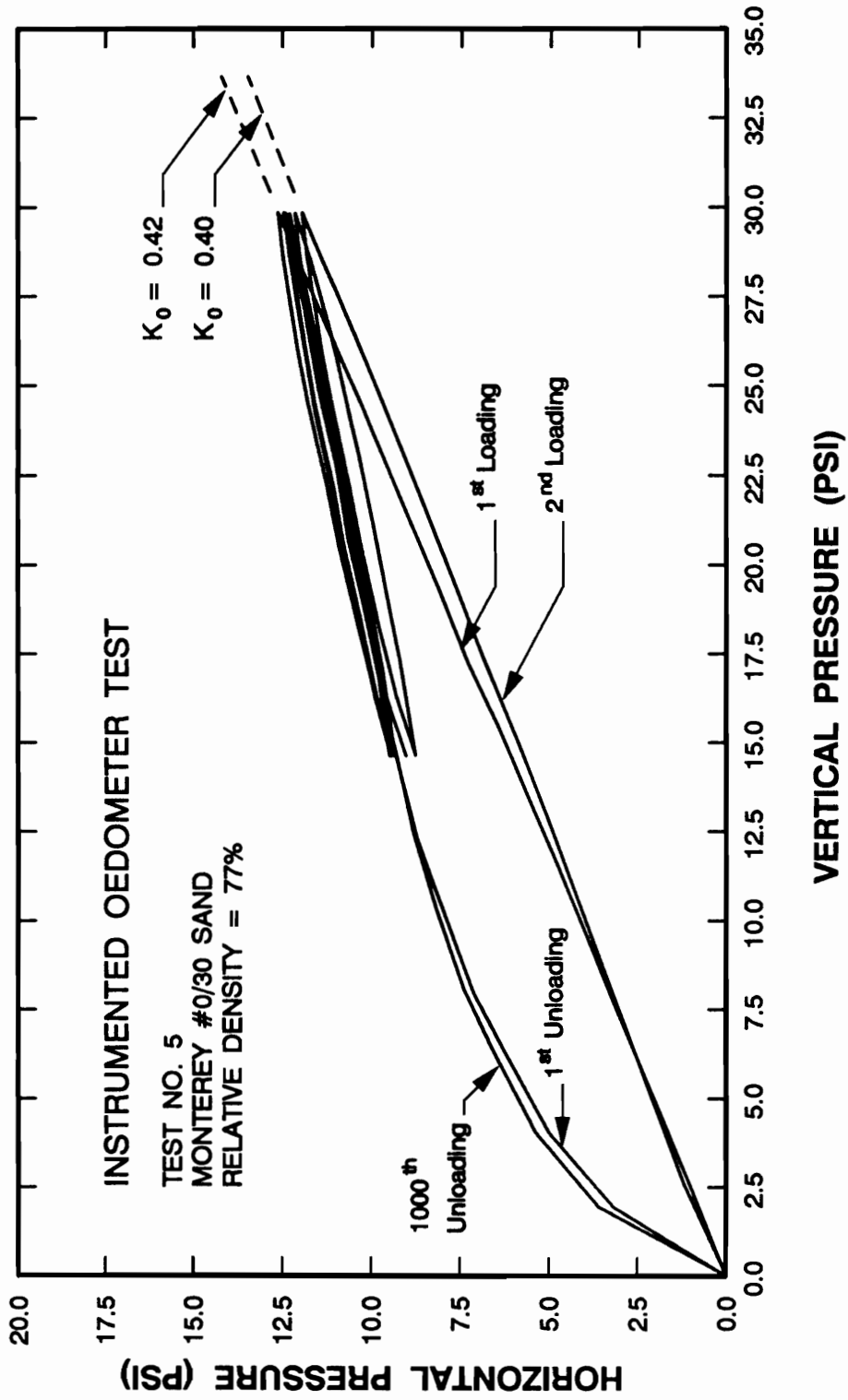


Figure 4.10) Results of a Multicycle K_0 Test on Monterey #0/30 Sand, Test Number 5.

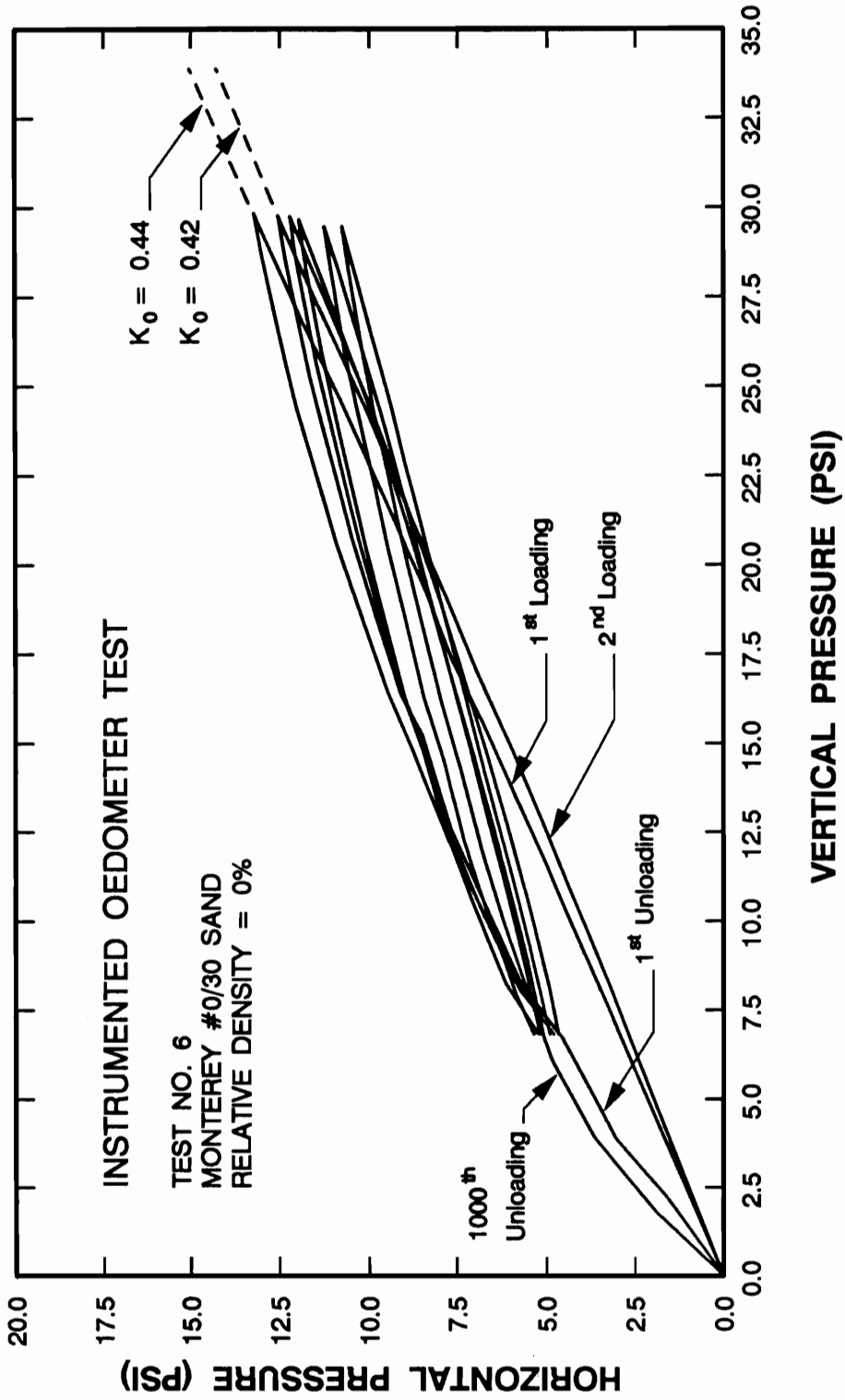


Figure 4.11) Results of a Multicycle K_0 Test on Monterey #0/30 Sand, Test Number 6.

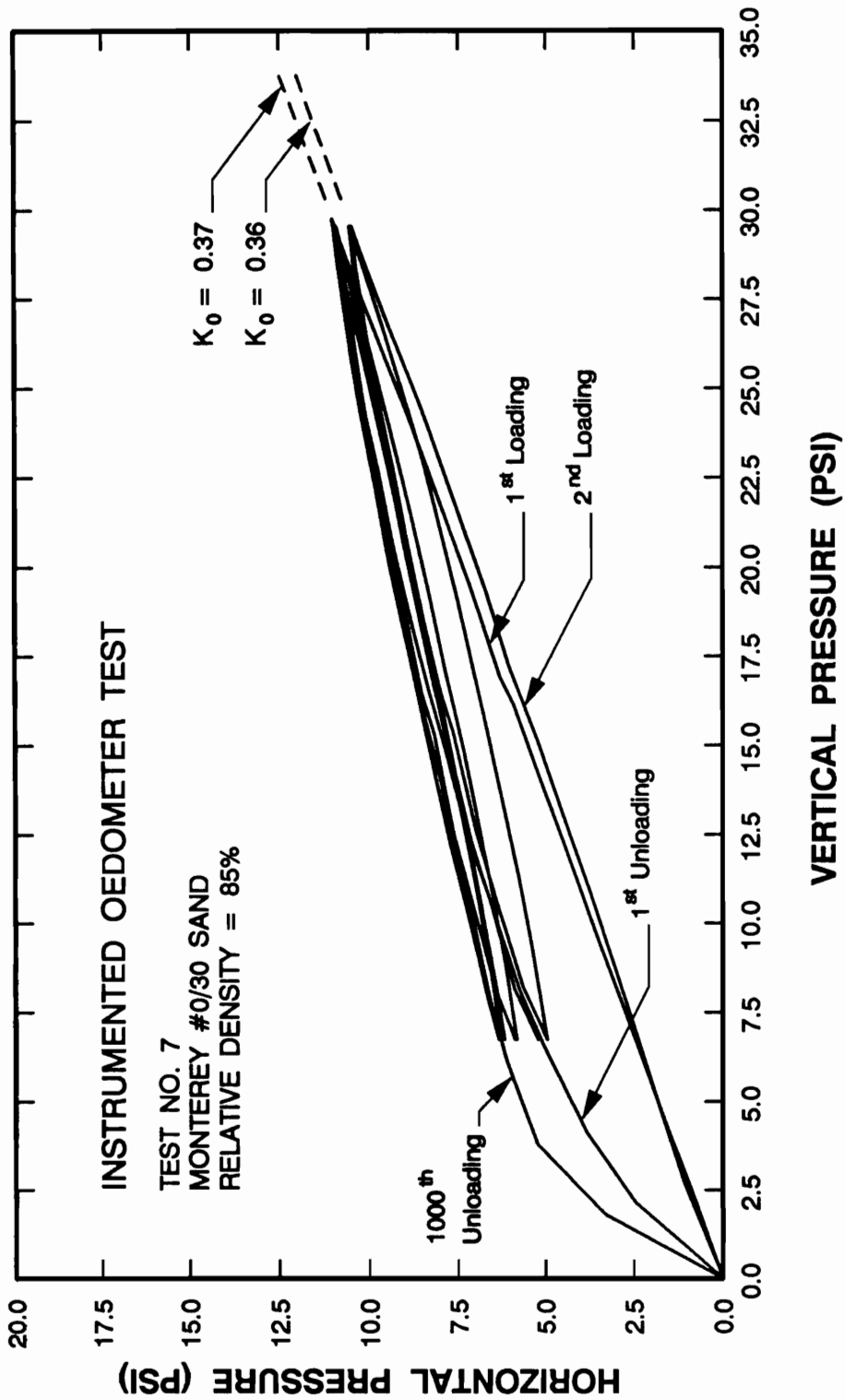


Figure 4.12) Results of a Multicycle K_0 Test on Monterey #0/30 Sand, Test Number 7.

The specimen for test 7 was deposited in the same manner and subsequently vibrated to increase its density.

After complete unloading from the first load cycle, the specimens were reloaded to the same peak vertical pressure used for the first load cycle. The K_0 values observed during the second loading cycle were lower than those of the first cycle for all four of the tests. The reduction in K_0 ranged from 0.01 for the densest sample of the group (test number 7) to 0.03 for the loosest sample of the group (test number 3). The linearity of the relationship between the vertical pressure and horizontal pressure during the second loading cycle indicates that, for granular cohesionless materials, the effects of overconsolidation are almost completely removed by unloading to zero vertical stress. The first load cycle is believed to cause permanent vertical strain, resulting in a denser sample for subsequent loading cycles. The slight reduction in K_0 between the first and second loading cycles can be attributed to a small increase in strength associated with this densification.

The relationships between K_0 and the number of load cycles are shown in Figure 4.13 for an overconsolidation ratio (OCR) of 1.0, and in Figure 4.14 for an OCR of 4.0. The values of K_0 during load cycles 3 through 1000, for OCR = 1.0, are generally between the values established during the first two load cycles. At an OCR of 4.0, the values of K_0 decreased between the first and second load cycles, and increased during subsequent load cycles, reaching peak values between

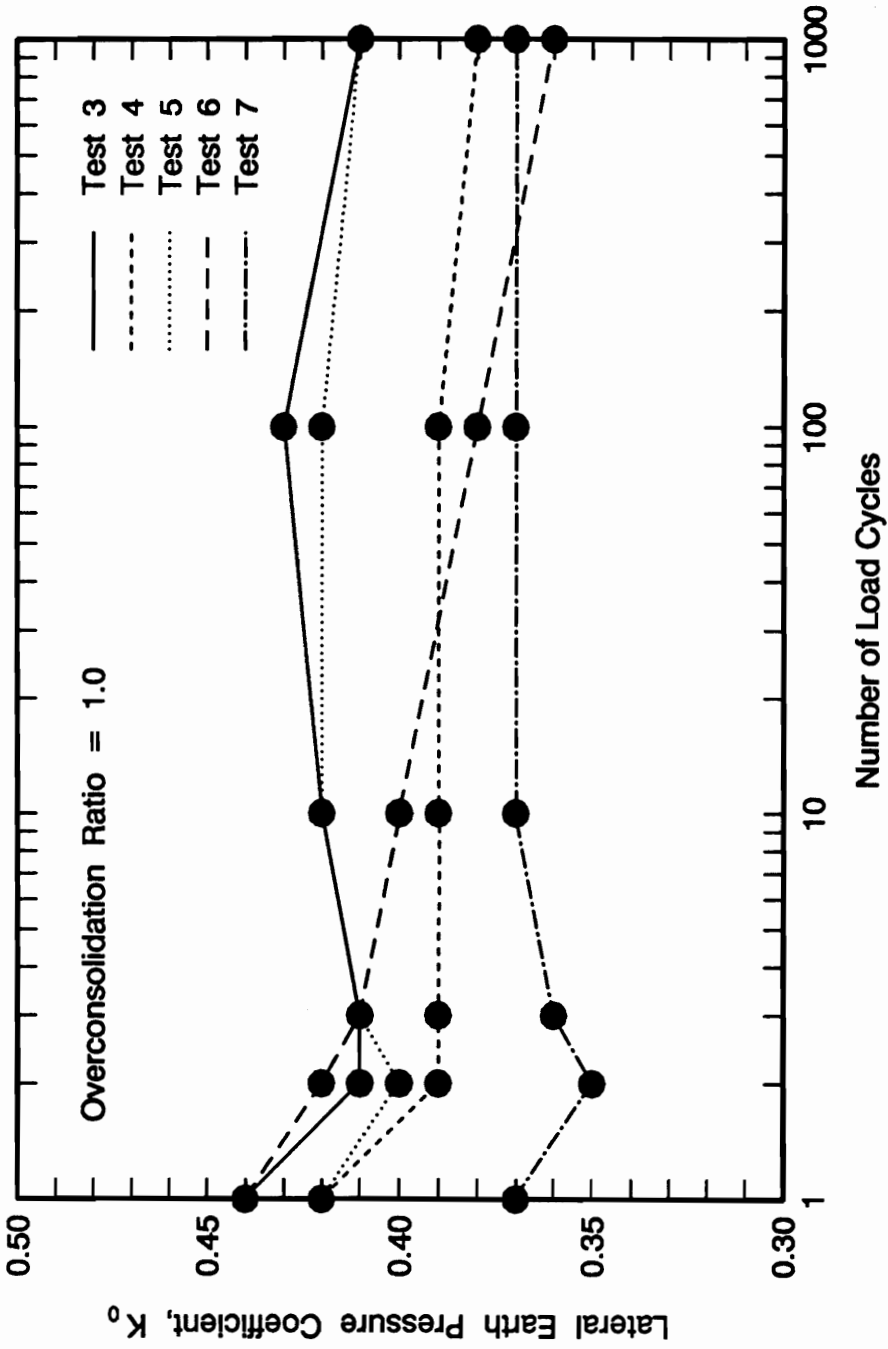


Figure 4.13) Relationships Between K_0 and Number of Load Cycles for an Overconsolidation Ratio of 1.0.

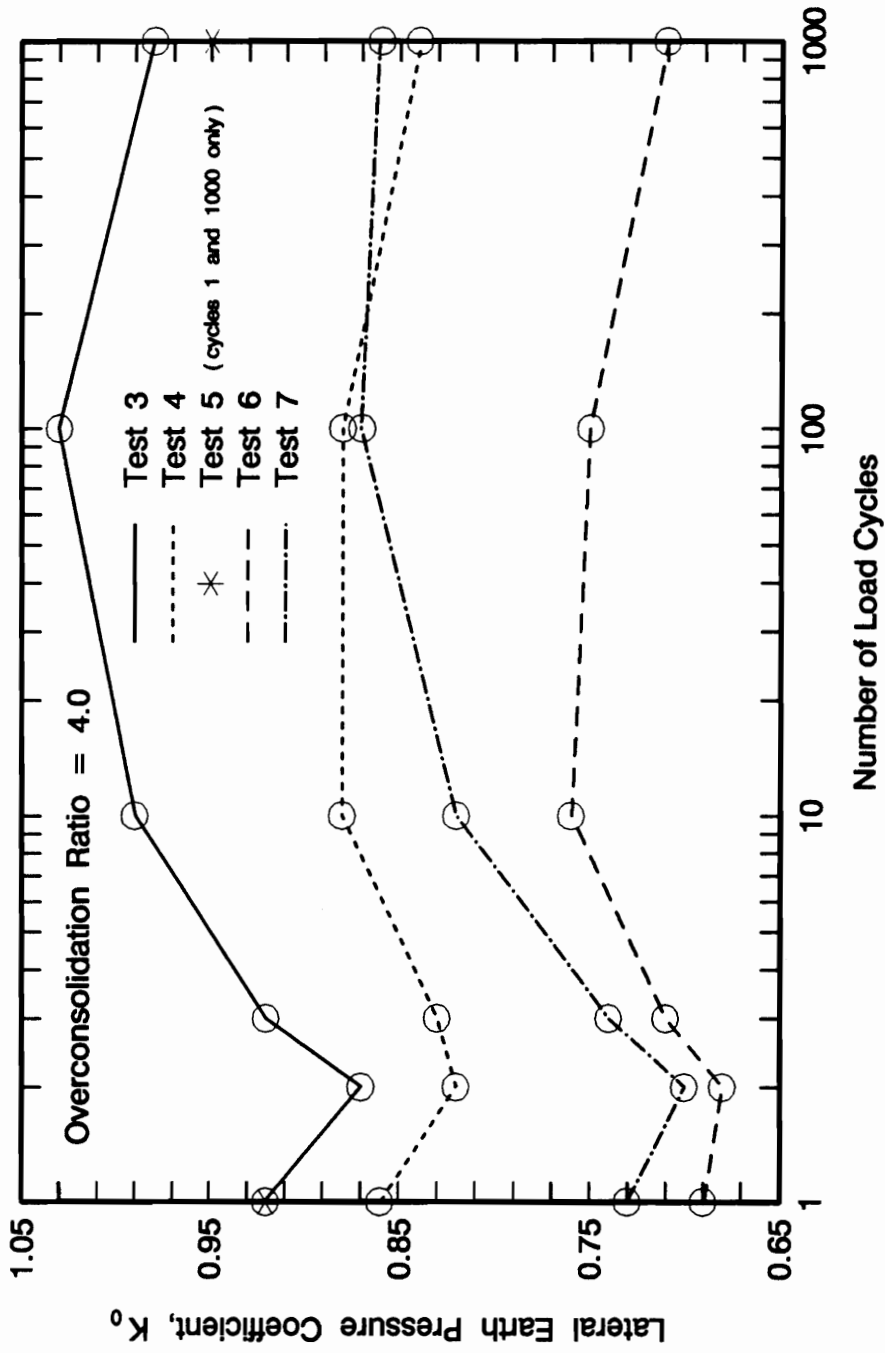


Figure 4.14) Relationships Between K_0 and Number of Load Cycles for an Overconsolidation Ratio of 4.0.

the 10th and 100th cycles. The values of K_0 generally decreases slightly from the peak values during the remaining 900 load cycles.

At an OCR of 10, K_0 during the 1000th unloading cycle was higher than during unloading for the 1st cycle. The amount of difference was greatest for tests 3 and 7, where the vertical pressure was cycled between about 6.5 lb/in² and 30 lb/in², and was smallest for test number 5, where the vertical pressure was cycling between about 14.5 lb/in² and 30 lb/in². For tests 3 and 7, the change in K_0 at an OCR of 10, after 1000 cycles, corresponded to an increase of about 25 to 30 percent. For test number 5, the increase in K_0 was less than 10 percent.

The initial density for test number 6 was very low, corresponding to a relative density of zero. In contrast with the behavior of the other four tests, the value of K_0 at an OCR of 1 continued to decrease as the number of load cycles increased. At an OCR of 10, the value of K_0 during the 1000th unload cycle was about 20% higher than during the first unloading cycle.

4.8 SUMMARY

An instrumented oedometer has been developed for investigation of the effects of large numbers of load cycles on the at-rest lateral earth pressure coefficient, K_0 . The oedometer is a split-ring device employing two load cells to monitor the horizontal pressure, and a pressure transducer to monitor the vertical pressure. A microcomputer-based data-acquisition and control system is used to record the data and to control the test.

The instrumented oedometer and the test control system have been tested and evaluated during this study and also by Samad (1988) and Knight (1988). During each of these evaluations, several improvements were made to the equipment and the test procedures, resulting in the system described in this chapter. The final system, under complete computer control, was used to perform five K_0 tests on Monterey #0/30 sand. Each test involved 1000 load/unload cycles.

The results of the multi-cycle K_0 tests indicate that, for relative densities between 75 and 85 percent, the effect of 1000 load cycles on the value of K_0 at an OCR of 1 was insignificant. At an OCR of 10, the 1000 load cycles produced an increase in K_0 ranging from a 9 percent to as much as 30 percent, depending on the degree of unloading from the peak pressure during the load/unload cycles. One test, on a very loose specimen, indicated a similar behavior at an OCR of 10, but at an OCR of 1 the value of K_0 continued to decrease with additional load/unload cycles, in contrast to the behavior of the specimens of higher density.

CHAPTER 5

INSTRUMENTED RETAINING WALL FACILITY

5.1 INTRODUCTION

The development of the Instrumented Retaining Wall Facility at the Price's Fork Research Station of Virginia Polytechnic Institute and State University (Virginia Tech) represents the primary effort of the research described in this report. The facility was developed to study the factors that control the magnitudes of earth pressures induced by compaction of soil. Previous investigations of earth pressures induced by compaction have shown that measuring earth pressures due to compaction is difficult because:

- 1) Earth pressure cells sometimes give erroneous readings, depending on their stiffness and how they are installed.
- 2) Compaction-induced earth pressures vary rapidly with depth, resulting in misinterpretation if fill elevations are not measured with sufficient accuracy.
- 3) There appears to be large inherent variability in earth pressures, resulting in possible erroneous evaluations if too few measurements are made.
- 4) Small wall movements can change earth pressures very significantly; walls must be stiff and mounted on unyielding supports to measure earth pressures that are not influenced by wall movements.

The experimental facility at Virginia Tech has been designed to overcome these problems, and to achieve accurate measurements of compaction-induced earth pressures at a scale approaching field scale.

The 7-ft-high by 10-ft-long instrumented retaining wall was constructed inside a very stiff reinforced concrete structure as shown in Figure 5.1. The bottom of the instrumented wall is 3 ft below floor level and the top is 4 ft above. The area in back of the wall, where the backfill is placed, is 6 ft wide. A 6-ft-wide ramp leading into the area provides access for loading and compacting equipment.

5.2 REACTION WALLS AND FLOOR

Lateral support for the instrumented wall is provided by a fifteen-inch-thick concrete wall, as shown in Figure 5.2. The two walls shown in Figure 5.2 are structurally connected to a 21-inch-deep floor slab to form a stiff reinforced concrete U-frame.

The structure was designed to limit the maximum outward deflection at the tops of the walls to 0.1 inches for the maximum design pressures. The design pressure distribution was triangular, starting at zero 1 ft below the top of the wall and increasing linearly to 3900 lbs/ft² at the base of the wall. The deflections were calculated using the methods of Section 9.5 of ACI Standard 318-77 (American Concrete Institute, 1981).

Construction drawings for the reinforced concrete structure and the access ramp are contained in Appendix C. The U-frame structure and the ramp were constructed by Debusk and Shelor, Inc. of Dublin, Virginia.

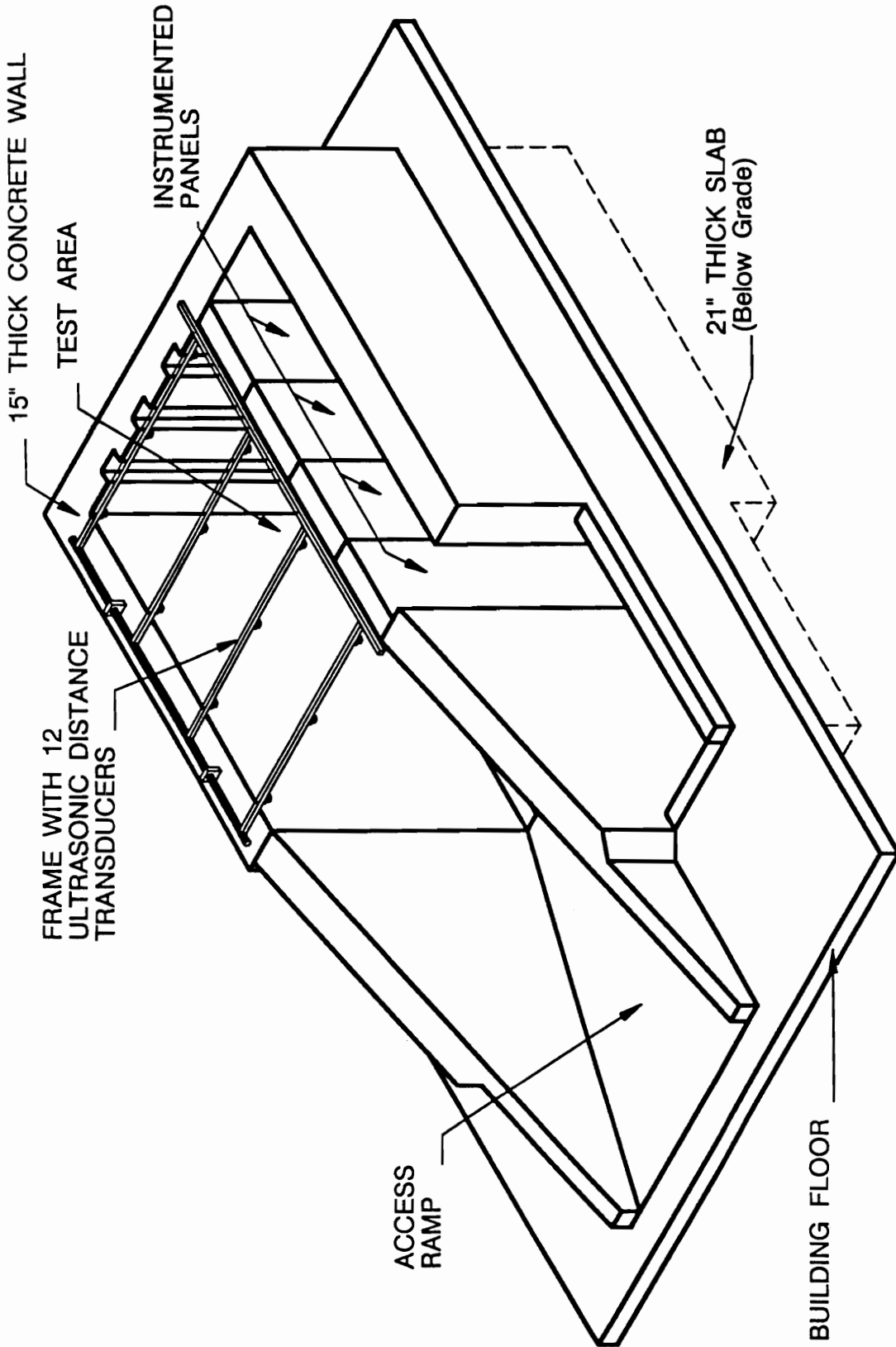


Figure 5.1) Instrumented Retaining Wall Facility.

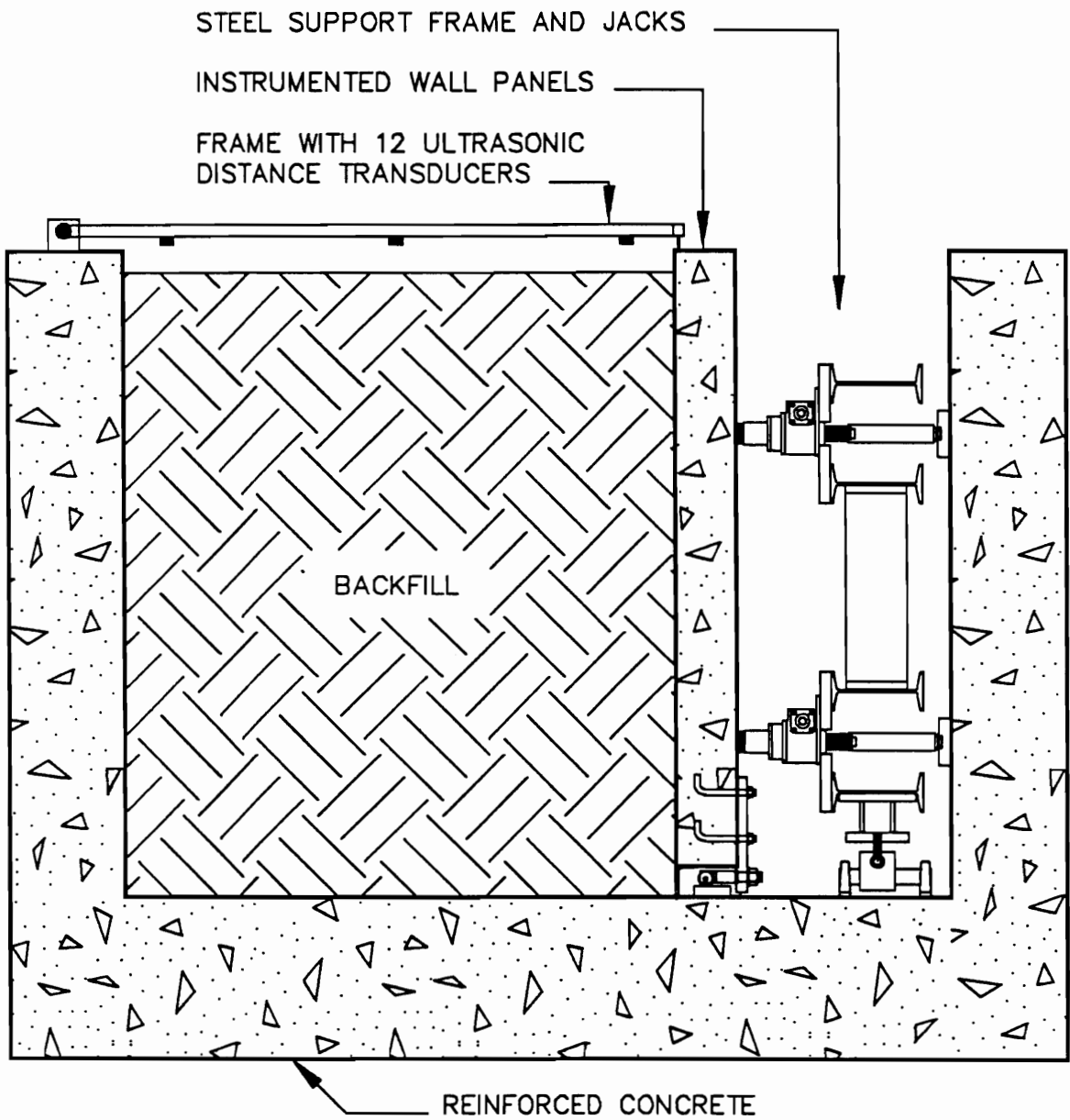


Figure 5.2) Instrumented Retaining Wall and Concrete Frame.

5.3 INSTRUMENTED PANELS AND POSITION CONTROL FRAME

The instrumented wall is divided into four panels, each 2.5 ft wide and 7 ft high, as shown in Figure 5.3. Each of these panels is mounted on two vertical load cells that support the weight of the panels and measure the vertical shear loads exerted on them by the backfill. Each panel is supported horizontally by three load cells, two located 20 inches above the bottom, and one located 60 inches above the bottom. These load cells are used to measure the magnitude and position of the resultant horizontal force exerted on each panel by the backfill.

All four wall panels are attached, through the horizontal load cells, to a stiff steel frame, as shown in Figure 5.2. The frame is supported vertically by bearings that can slide and rotate, and horizontally by jacks that can be used to induce translational or rotational movements. Because the frame is very stiff, the four wall panels always move together, remaining in the same plane.

5.4 TRANSDUCERS

A total of 64 transducers are used to record a variety of measurements, including earth pressures, vertical and horizontal forces, wall displacements, fill depths, and temperatures. All of the transducers are recorded using a microcomputer-based data-acquisition system. The data-acquisition system is controlled by a computer program developed during this study. The suppliers of the transducers and the data-acquisition hardware are listed in Table 5.1. The following

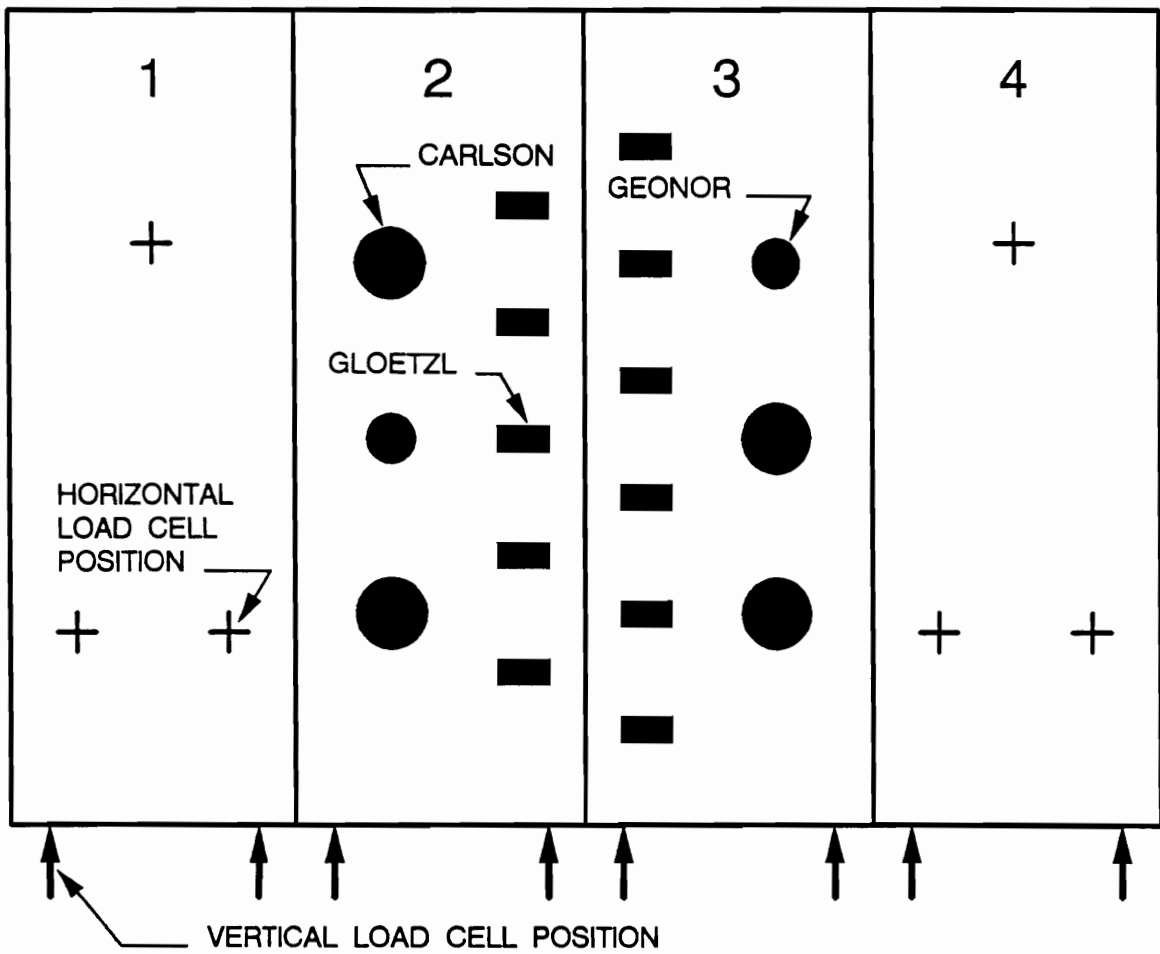


Figure 5.3) Instrumented Wall Panels of the Retaining Wall Facility.

Table 5.1) Suppliers of Instrumentation Hardware.

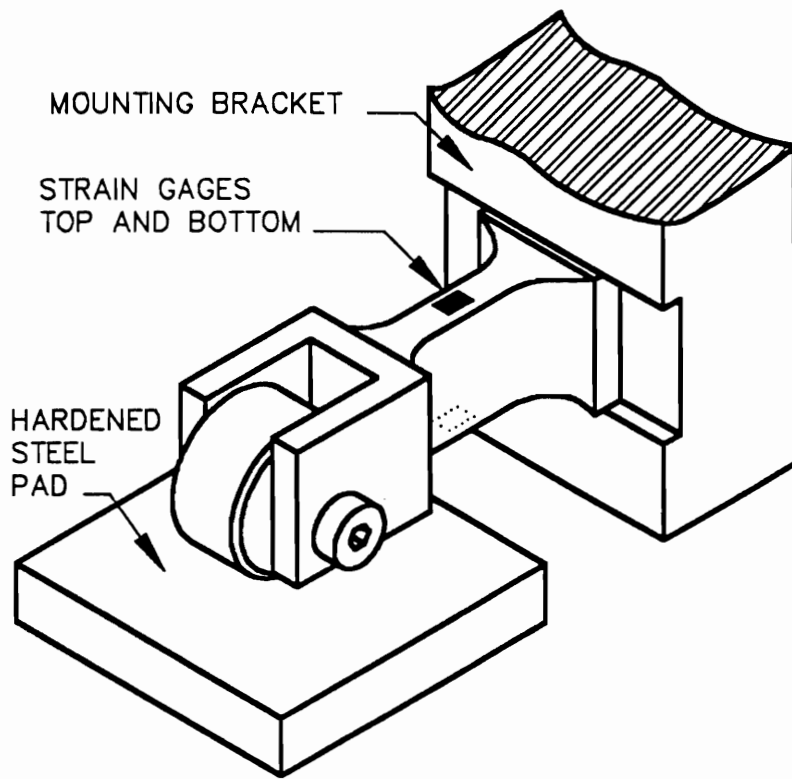
Item	Manufacturer
<p>Gloetzl Earth Pressure Cells Type: E 7/14 K3.5 Z4 Model: C, with adaptor for Omega pressure transducers, special order</p>	<p>Gloetzl Gesellschaft fur BaumeBtechnik GmbH 7512 Rheinstetten 4-Fo. WEST GERMANY</p> <p>US Representative: Geo Group, Inc. 2209 Georgian Way #12 Wheaton, MD 20902</p>
<p>Carlson Earth Pressure Cells Model: S-25</p>	<p>Carlson/RST Instruments 1190-C Dell Avenue Campbell, CA 95008</p>
<p>Geonor Earth Pressure Cells Model: P100, 0 to 5 Bar</p>	<p>Geonor A/S P. O. Box 99 - ROA 0701 Oslo 7 NORWAY</p> <p>US Representative: Geonor, Inc. 1454 Van Houten Ave. Clifton, NJ 07013</p>
<p>Ultrasonic Distance Measuring Devices and Interfacing Hardware</p>	<p>Contaq Technologies Corp 15 Main Street Bristol, VT 05443</p>
<p>LVDTs Models: 353-000 351-000</p>	<p>Trans-Tek, Inc. Route 83 P. O. Box 338 Ellington, CT 06029</p>
<p>Pressure Transducers, Model: PX236 (used with Gloetzl cells) Thermocouples, type T</p>	<p>Omega Engineering, Inc. One Omega Drive Stamford, CT 06907</p>
<p>Data Acquisition Hardware Models: DAS-8, EXP-16, CTM-05</p>	<p>MetraByte Corporation 440 Myles Standish Blvd. Taunton, MA 02780</p>

sections discuss the transducers and the data-acquisition hardware and software.

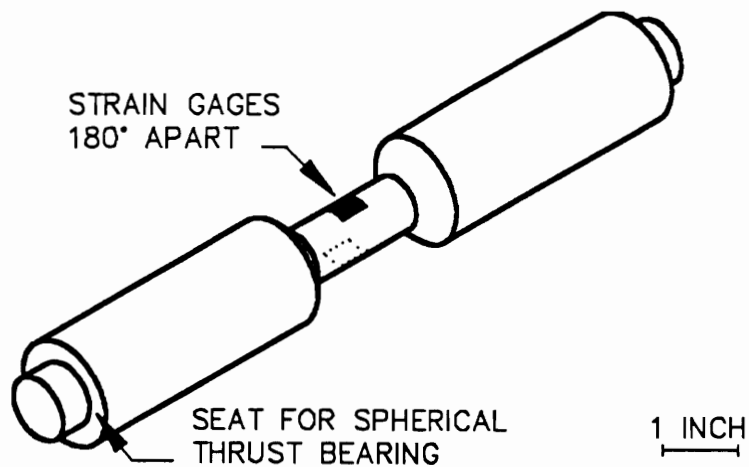
5.4.1 Force Transducers

The vertical forces on the wall panels are measured by means of the load cells that support the panels. As shown in Figure 5.4, these load cells are 4-inch-long cantilever beams bolted to brackets at the bottoms of the panels. The free end of each beam has a roller bearing wheel that can move back and forth on a hardened steel pad epoxied to the concrete floor. This permits free lateral movement of the wall panels. The vertical forces are measured by means of bonded strain gages attached to the cantilever beams. The four active strain gages are connected in a standard Wheatstone bridge configuration such that the load cell is sensitive to vertical bending and insensitive to lateral bending, axial compression, and temperature changes. Further reduction of temperature effects is provided by using temperature compensating gages. The accuracy of the load cells is about ± 15 pounds, or about ± 30 pounds per panel.

The horizontal reaction forces on the wall panels are measured using column load cells with bonded strain gages. As shown in Figure 5.4, the ends of the columns are seated in spherical bearings to minimize bending. The four active strain gages are connected in a standard Wheatstone bridge configuration such that the load cell is sensitive to axial load and insensitive to bending and temperature changes. Further reduction of temperature effects is provided by using temperature



VERTICAL LOAD CELL



HORIZONTAL LOAD CELL

Figure 5.4) Vertical and Horizontal Load Cells.

compensating gages. The accuracy of the load cells is about ± 50 pounds, resulting in an overall accuracy of about ± 150 pounds for the horizontal force on a single wall panel. With two load cells at the bottom of each panel and one at the top, it is possible to determine both the magnitude and the position of the resultant force acting on each panel. Comparing these to the same quantities determined from the earth pressure cell readings provides an independent check on accuracy.

The horizontal load cells work only in compression. During the early stages of filling, when fill is being placed and compacted below the bottom load cells, the top load cells tend to go into tension, and become loose in their bearings. To prevent this, they are prestressed in compression by springs located at the top and 2 ft above the bottom of the wall panels. These springs hold the horizontal load cells in compression during the early stages of backfilling, before they are loaded in compression by the earth pressure forces. The load cells are so much stiffer than the compression springs that there is no appreciable change in the spring forces as the forces in the load cells change.

The horizontal and vertical force transducers are made of 17-4 PH[®] stainless steel that was machined in Condition A (solution treated) and subsequently heat treated to condition H-925 (Armco, Inc., 1986). This material is well suited for use as force transducer elements because its load-deformation response exhibits high linearity, low hysteresis, and low creep, because it is easily machined and heat treated, and because

it is readily available at an economical cost (Measurements Group, Inc., 1983).

5.4.2 Earth Pressure Cells

A total of 17 earth pressure cells (11 Gloetzl cells, 4 Carlson cells, and 2 Geonor cells) are mounted on the center two wall panels, as shown in Figure 5.3. These pressure cells are all quite stiff, and are mounted flush with the faces of the wall panels. They are located at 6.0 inch vertical spacings in four vertical strips on the two wall panels. They thus provide closely spaced points for determining variations of earth pressure with depth, and redundancy with respect to pressure cell elevation and pressure cell type.

5.4.2.1 Gloetzl Earth Pressure Cells

The Gloetzl earth pressure cells consist of two rectangular steel plates, welded together around their edges, with a thin film of oil between them, as shown in Figure 5.5a. They are 14 cm long, 7 cm wide, and 0.45 cm thick. Their front faces are flat. The oil pressure is transmitted to a pressure transducer by means of a heavy gage steel tube that extends from the back of the cell. The cells used in the Retaining Wall Facility were fitted with electrical pressure transducers so that they could be read using the data-acquisition system. The transducers were purchased in the United States and were attached to the pressure cells at the Gloetzl factory in Germany.

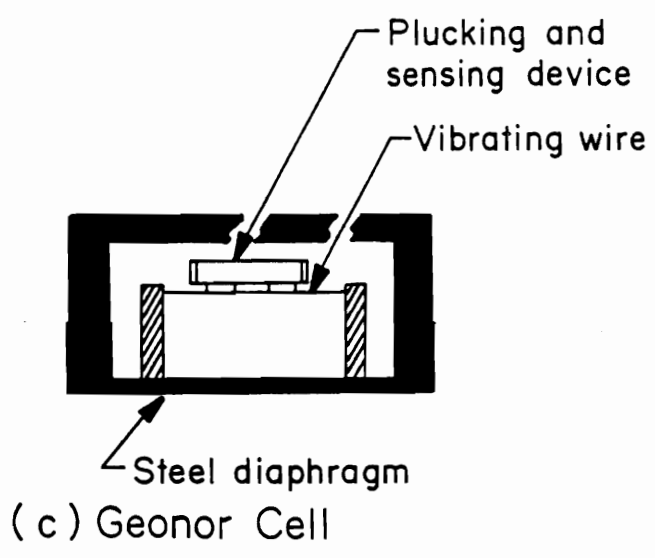
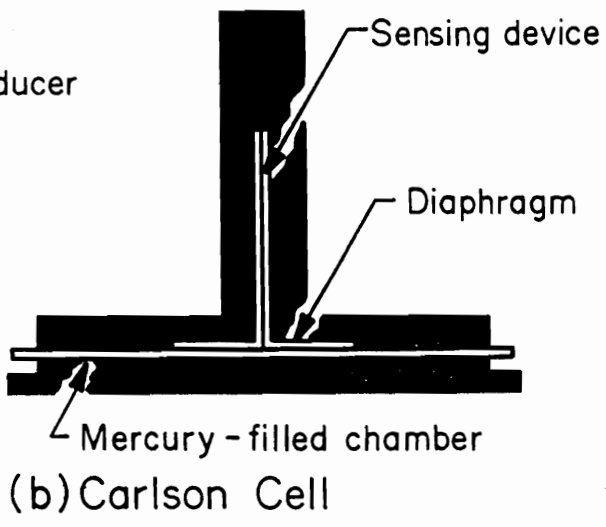
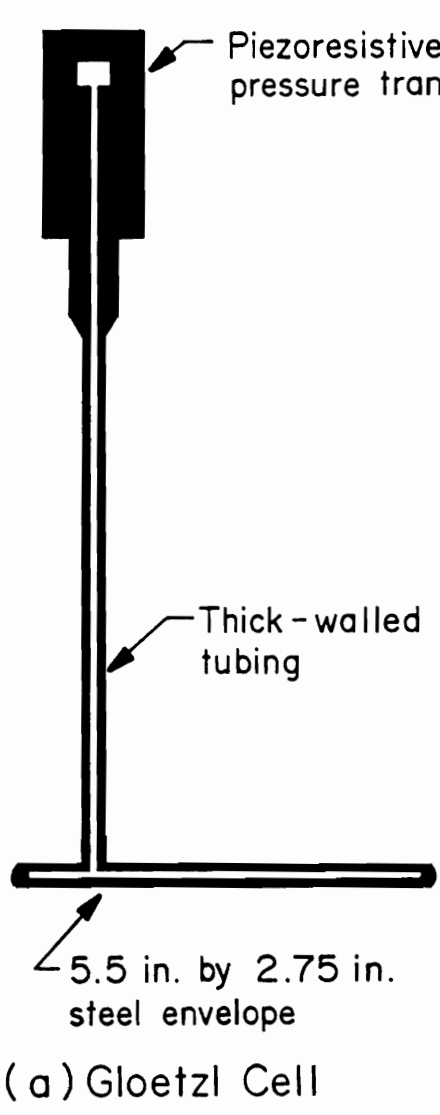


Figure 5.5) Earth Pressure Cells.

5.4.2.2 Carlson Earth Pressure Cells

The Carlson earth pressure cells are 7.4 inches in diameter and about 1 inch thick, as shown in Figure 5.5b. Behind a heavy metal face-plate they contain a thin film of mercury. The pressure in the mercury is determined by measuring the deflection of a diaphragm using an extensometer contained in a cylindrical housing attached to the back of the cell. The pressure readings are sensitive to the temperature of the cell, and the temperature is measured each time a pressure reading is made.

5.4.2.3 Geonor Earth Pressure Cells

The Geonor earth pressure cells are 16.5 cm in diameter and 4.6 cm thick. As shown in Figure 5.5c, the faces of the cells are stiff metal diaphragms. The diameter of the active portion of this diaphragm is 7.5 cm. Attached to the back of the diaphragm is a taut wire which is caused to vibrate at its natural frequency by an electrical magnet that is switched on and off at intervals. As the pressure on the face of the cell changes, the tension in the wire and the natural frequency of its vibration also change. The vibration of the wire is monitored up by a small pickup device in the cell, and transmitted as an electrical signal to the data-acquisition system. The frequency of vibration is determined by counting the number of signal pulses during a one-second time interval.

5.4.3 Displacement Transducers

Movements of the wall panels are measured by 8 Linear Variable Differential Transformers (LVDTs), one near the top and one near the bottom of each wall panel. The LVDTs are mounted on unstressed reference frames attached to the reinforced concrete wall that supports the steel frame. A ninth LVDT, mounted on the floor slab of the building, is used to measure possible movements of the reinforced concrete wall. The floor slab is isolated from the concrete wall by an expansion joint.

The LVDTs are powered by direct current. Their range of measurement is 1.0 inch. If the output nonlinearities of the LVDTs are accounted for, accuracies on the order of 0.0005 inches are achievable.

5.4.4 Distance Transducers

The elevation of the surface of the fill is measured, after each lift is compacted, using an array of 12 Ultrasonic Distance-Measuring Devices (UDMDs) mounted on a frame that rotates down into a horizontal position over the fill. The frame is shown in Figures 5.1 and 5.2. The UDMDs can sense the position of the fill after compaction, but they cannot be used to measure the position of the loose fill, because the ultrasonic signals are scattered rather than reflected from the loose fill.

As illustrated in Figure 5.6, the UDMDs send out a burst of ultrasound at a single frequency, and measure the length of time for the first reflected wave to reach the instrument. This interval of time, divided by the speed of sound, is twice the distance from the instrument

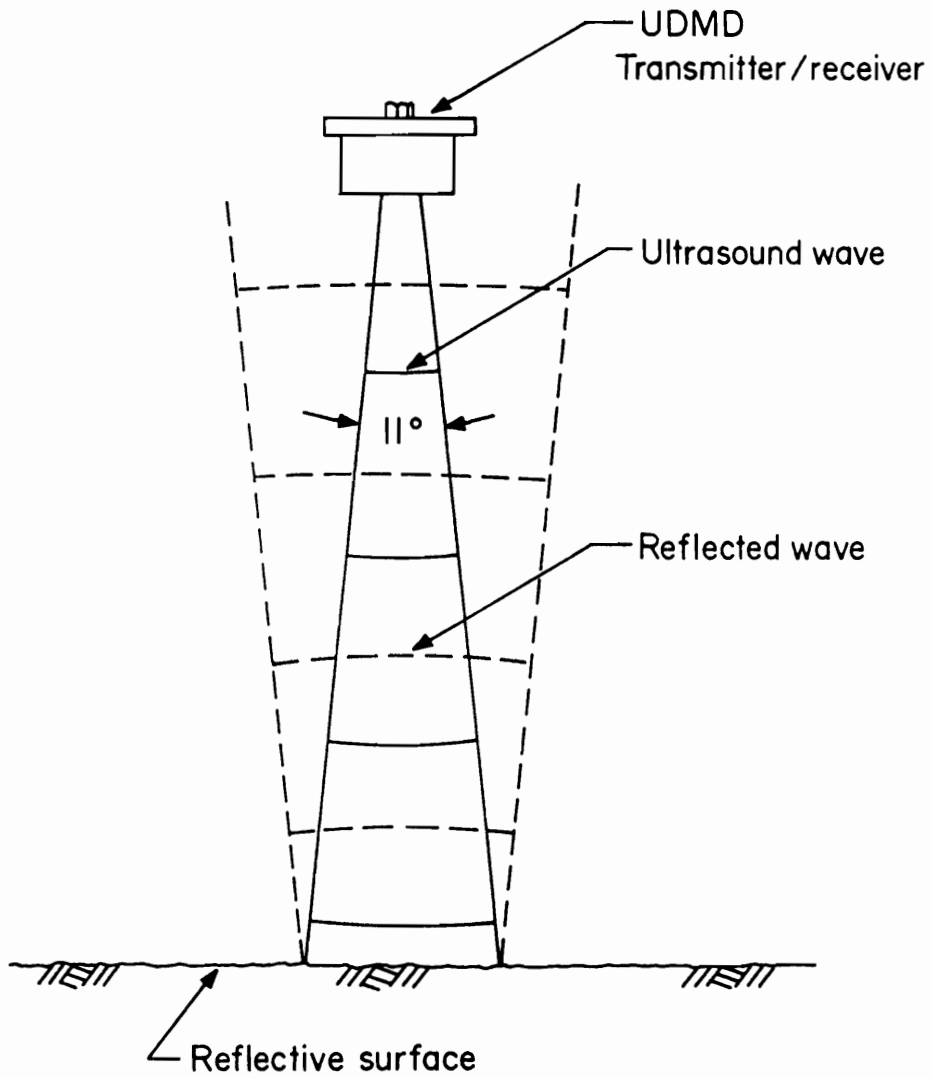


Figure 5.6) Ultrasonic Distance-Measuring Device.

to the surface causing the reflection. The maximum range of the UDMDs is about 30 ft, which is considerably longer than required for this application.

5.4.5 Temperature Sensors

Two thermocouples are used to measure the temperature of the LVDT support, to determine possible temperature effects on the readings.

The temperature of the wall panels is measured at three locations, one near the bottom of the wall, one near the middle, and one near the top. These measurements provide the information needed to adjust the Gloetzl cell readings for temperature-induced zero shift.

The thermocouples are conventional copper-constantan devices capable of measuring temperature with an accuracy of ± 0.5 degree Fahrenheit.

5.5 DATA-ACQUISITION HARDWARE

The instruments used in the Instrumented Retaining Wall Facility can be separated into four groups by the type of measurement used to read them. The signal groups are: 1) direct current voltage, 2) resistance, 3) frequency, and 4) time interval. All of the measurements are recorded using the same microcomputer-based data-acquisition system. The force transducers, Gloetzl cells and thermocouples output direct-current voltage signals that are monitored using commercially available analog-to-digital conversion components. The Carlson cell, a resistance instrument, is read by connecting the instrument resistors in series with precision resistors of known resistance, energizing the circuit,

measuring the voltage at various points in the circuit using the analog-to-digital conversion system, and calculating the instrument resistance. The Geonor cells produce a variable frequency waveform. The frequency of the waveform is measured using commercially available frequency-to-digital conversion components. The UDMDs require a time-interval measurement, and are monitored using a proprietary system that was purchased with the instruments.

Each of the data-acquisition hardware systems are discussed in the following sections.

5.5.1 Analog-to-Digital System

Each of the instruments that produce a voltage signal are monitored through the analog-to-digital system. The hardware for the analog-to-digital system includes a MetraByte DAS-8, seven MetraByte EXP-16s, and a microcomputer. The same microcomputer is used for all of the data-acquisition subsystems.

The MetraByte DAS-8 is an analog-to-digital (A/D) conversion system in the form of a plug-in expansion card for IBM-PC or IBM-PC compatible microcomputers. The DAS-8 has a single A/D conversion circuit that is multiplexed to 8 analog input channels. An analog input signal between +5 VDC and -5 VDC is converted by a 12 bit A/D converter providing a resolution of 1 part per 4096 parts ($1/2^{12}$), corresponding to a voltage resolution of about 2.4 millivolts. The DAS-8 also provides four digital output lines that can be used to address the EXP-16 sub-multiplexor. The status of the eight channel multiplexor on the

DAS-8 and the four digital output lines, used to control the sub-multiplexor of the EXP-16, is under software control through the microcomputer's I/O space.

The EXP-16 is a 16 channel sub-multiplexor with 8 switch-selectable gains and a cold-junction compensation circuit for use with thermocouples. A maximum of eight EXP-16 units can be connected to a single DAS-8 A/D card using a daisy-chain cabling system.

One input line on the DAS-8 is dedicated to each of the EXP-16 cards. The cold-junction compensation circuit on the EXP-16 also requires one DAS-8 input line, reducing by one the number of EXP-16 cards that can be connected to the DAS-8.

The system used for the Instrumented Retaining Wall Facility consists of one DAS-8 and seven EXP-16s. The cold-junction compensation circuit of the seventh EXP-16 is connected to the eighth input channel of the DAS-8. This configuration provides 112 double-ended analog inputs and one cold-junction compensation circuit.

5.5.2 Control Relay Board for Carlson Cells

The Carlson cell is a resistance instrument with two resistive elements, as shown in Figure 5.7. In addition to the two instrument resistances, R_1 and R_2 , there are three lead wire resistances. The lead wire resistance, R_c , is the same for each of the lead wires.

In order to monitor the Carlson cells with the analog-to-digital data-acquisition system, a system of relay switches and precision resistors was developed. The relay/resistor circuit shown in Figure 5.8

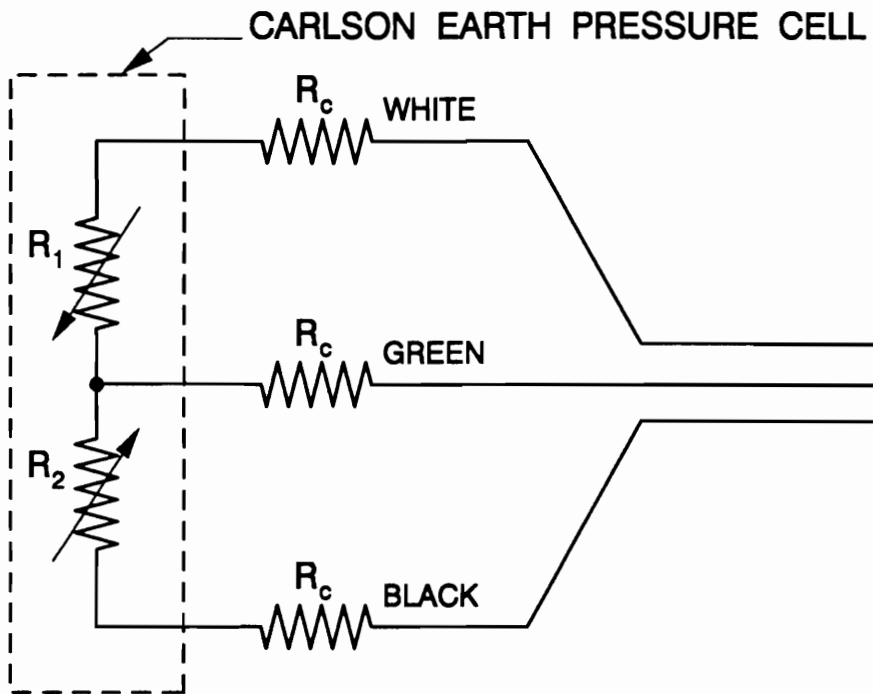


Figure 5.7) Instrument and Lead Wire Resistances of the Carlson Earth Pressure Cell.

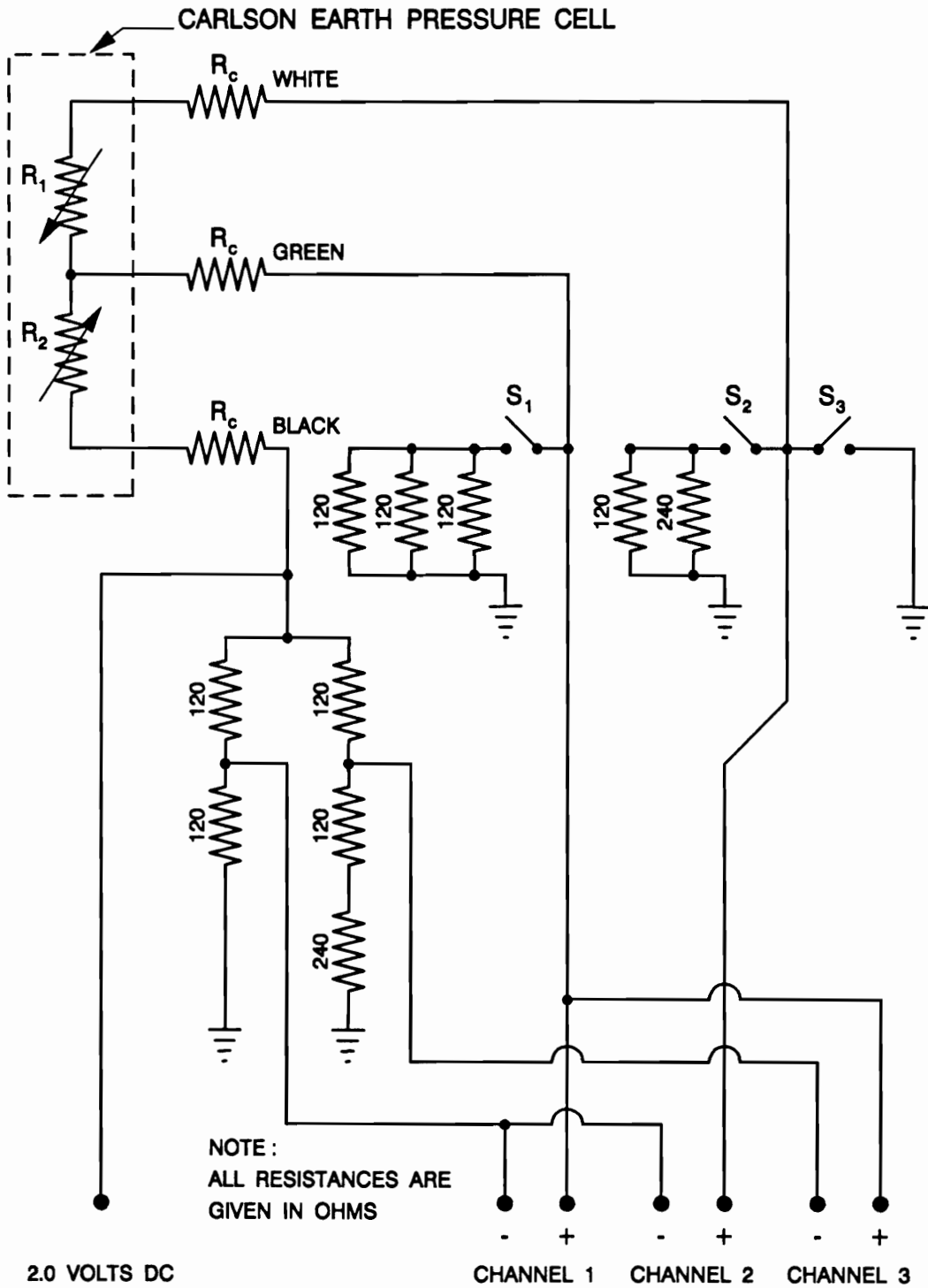


Figure 5.8) Resistor/Relay Circuit used to Interface the Carlson Earth Pressure Cells with the Data-Acquisition System.

is used to connect the resistances of a Carlson instrument with precision resistors to form four different circuits. The status of relay switches S_1 , S_2 , and S_3 used to produce the four different circuit configurations is indicated in Table 5.2, along with the output channel recorded for each configuration.

A relay/resistor system capable of supporting four Carlson cells was developed based on the single instrument system shown in Figure 5.8. The four-instrument system uses a four-bit decoder to control sixteen relay switches. Four digital output lines of the MetraByte CTM-05 are used to control the relay switches via the four bit decoder of the relay/resistor system. During a data sampling cycle, relay switch configuration and data channel selection are controlled by the software.

Based on the information in Figure 5.8 and Table 5.2, and the measured voltages, the values of $(R_1 + R_2)$ and (R_1/R_2) are calculated. These values are used with the calibration information to determine the pressure exerted on the face of the Carlson instrument and the temperature of the instrument.

5.5.3 Frequency-to-Digital System

A MetraByte CTM-05 frequency-to-digital expansion card installed in the microcomputer is used to monitor the pressure-dependent frequency of the Geonor earth pressure cells. Upon instruction from the microcomputer, the CTM-05 counts the number of cycles of the input signal for the desired time interval. The frequency of the input signal

Table 5.2) Circuit Configurations Used to Read the Carlson Earth Pressure Cells.

Circuit Config.	Switch Status			Data Channel Recorded		
	S ₁	S ₂	S ₃	Chan. 1	Chan. 2	Chan. 3
1	open	open	closed	XX		
2	open	closed	open		XX	
3	open	closed	open			XX
4	closed	open	open	XX		

is determined by dividing the number of cycles counted by the length of the time interval during which the count is made.

The output signal frequency of the Geonor earth pressure cells ranges from about 1.1 kHz to about 2.0 kHz. When a sampling interval of 1 second is used, the error of the measured frequency is less than ± 0.1 percent.

The CTM-05 also provides four digital output lines which are used to control the relay/resistor unit used with the Carlson earth pressure cells.

5.5.4 Distance Transducer Monitoring System

The ultrasonic distance measuring devices are monitored using a UDM-PC and a UDM-MUX purchased with the measuring devices. The UDM-PC is an expansion card that is installed in the microcomputer and the UDM-MUX is a 14 channel multiplexor that expands the number of UDMDs that can be connected to the UDM-PC system from 1 to 14. User manuals by Contaq Technologies Corporation (1987 and 1986) contain detailed information on the operation of the UDM-PC and the UDM-MUX.

As used in the Instrumented Retaining Wall Facility, the interaction between the data-acquisition program and the distance-measuring system is via assembly language subroutines obtained from Contaq Technologies Corporation.

5.5.5 Personal Computer and Power Supply

The microcomputer used for data acquisition is an IBM-XT with 640 kilobytes of system memory, 1 floppy disk drive, and a 10 megabyte hard disk. The data-acquisition expansion cards are installed in the computer and connected to the multiplexers or instruments by cables as described above.

A Topward Model 2203 power supply provides the direct current supply voltage required by the instrumentation system. The power supply has a maximum output of three amps, and is adjustable from 0 to 20 volts DC. Before recording each data set, the supply voltage is checked using a digital multimeter, and is adjusted to 10.404 ± 0.002 volts DC. The value of 10.404 is used because many of the instruments were calibrated using a power supply that produced this voltage. Due to the complexity of the overall instrumentation circuit, it was advantageous to continue using the same supply voltage.

5.6 DATA-ACQUISITION SOFTWARE

The computer program EP.BAS which controls the data-acquisition procedures is written using Microsoft QuickBASIC 4.5. The program utilizes proprietary routines provided with the various data-acquisition components (MetraByte Corporation, 1984, 1985a, and 1985b and Contaq Technologies Corporation, 1986 and 1987). The proprietary routines and QuickBASIC 4.5 were used to create a Quick Library that is linked with the program EP.BAS during compilation to create the stand-alone executable file EP.EXE. Listings of the data-acquisition program EP.BAS

and the input data file MASTER.ZZZ are contained in Appendix B along with a brief description of the function of each of the subroutines in EP.BAS.

The program has two principal modes of operation: one for the first set of data from an earth pressure test and the other for all subsequent data sets. During acquisition of the first data set (the zero readings), the program prompts the user to enter various pieces of information to be included in the data file header, and to confirm or correct the date and time settings of the computer. The program then reads the calibration information from the file MASTER.ZZZ and instructs the operator to adjust the supply voltage. Upon the instruction to continue, the output signal of each instrument is read and stored in the user specified data file. The data file name is also appended to the file MASTER.ZZZ. This set of data represents the zero readings of the instruments. These values are subtracted from future readings to provide the measured values.

During subsequent executions of EP.EXE for the same test, the operator indicates that the instrument readings are to be appended to the most recently used data file as test data values. The program then performs the following tasks: 1) calibration factors and the name of the most recently used data file are read from file MASTER.ZZZ, 2) zero readings for each of the instruments are read from the data file, and 3) the operator is prompted to adjust the instrumentation voltage supply and supply the command to continue when ready. Upon receiving the command, the program addresses each of the instruments via the data-

acquisition hardware and records the value of the output signal. The zero readings are subtracted from the data readings and the resulting values are converted to engineering units and written to the data file. A complete set of readings can be recorded, converted to engineering units, and written to the data file in less than 3 minutes.

5.7 CALIBRATION

The procedure used to calibrate a transducer and the form of the calibration factor depend on the transducer type and the data-acquisition method used for that transducer. With the exception of the UDMDs, all of the transducers were calibrated prior to use, under the same conditions that exist in the final installation. The factors held constant include excitation voltage, excitation and signal lead lengths, shielding, data-acquisition hardware, data-channel assignment, and cable connectors. The UDMDs are calibrated during each set of readings, as described later.

5.7.1 Force Transducers

The horizontal and vertical force transducers were calibrated in the lab under controlled conditions to evaluate their individual performance and in the Experimental Retaining Wall Facility to verify the lab calibration factors and to evaluate the degree of interaction between wall panels, if any.

In the lab calibration, the horizontal and vertical load cells were loaded using a universal testing machine. During calibration, the data

from the transducer being calibrated and from the reference load cell were recorded using the same data-acquisition equipment used in the Instrumented Retaining Wall Facility.

Each vertical load cell was subjected to fifty load/unload cycles between 100 and 4500 pounds and was subsequently calibrated between 0 and 3000 pounds using one load/unload cycle. A typical calibration result is shown in Figure 5.9. The highly linear response and the lack of hysteresis are typical of the vertical load cells and of the horizontal load cells.

The horizontal load cells were calibrated with the same procedure, except that the load/unload cycles were between 500 and 10000 pounds and the calibration range was 0 to 5000 pounds.

It is convenient to represent the calibration factors in terms of pounds per bit because the information obtained from the data-acquisition system is in terms of bits. This procedure minimizes the number of computations required to convert the measurements to engineering units. Table 5.3 lists the calibration factors for the force transducers. The zero intercept of the calibration curves are not needed because zero readings are obtained at the beginning of each test.

The calibration factors of the horizontal and vertical force transducers were also checked after the transducers were installed in the Retaining Wall Facility. The horizontal load cells were found to underregister by about 3 to 5 percent and the vertical load cells underregistered by about 6 to 9 percent.

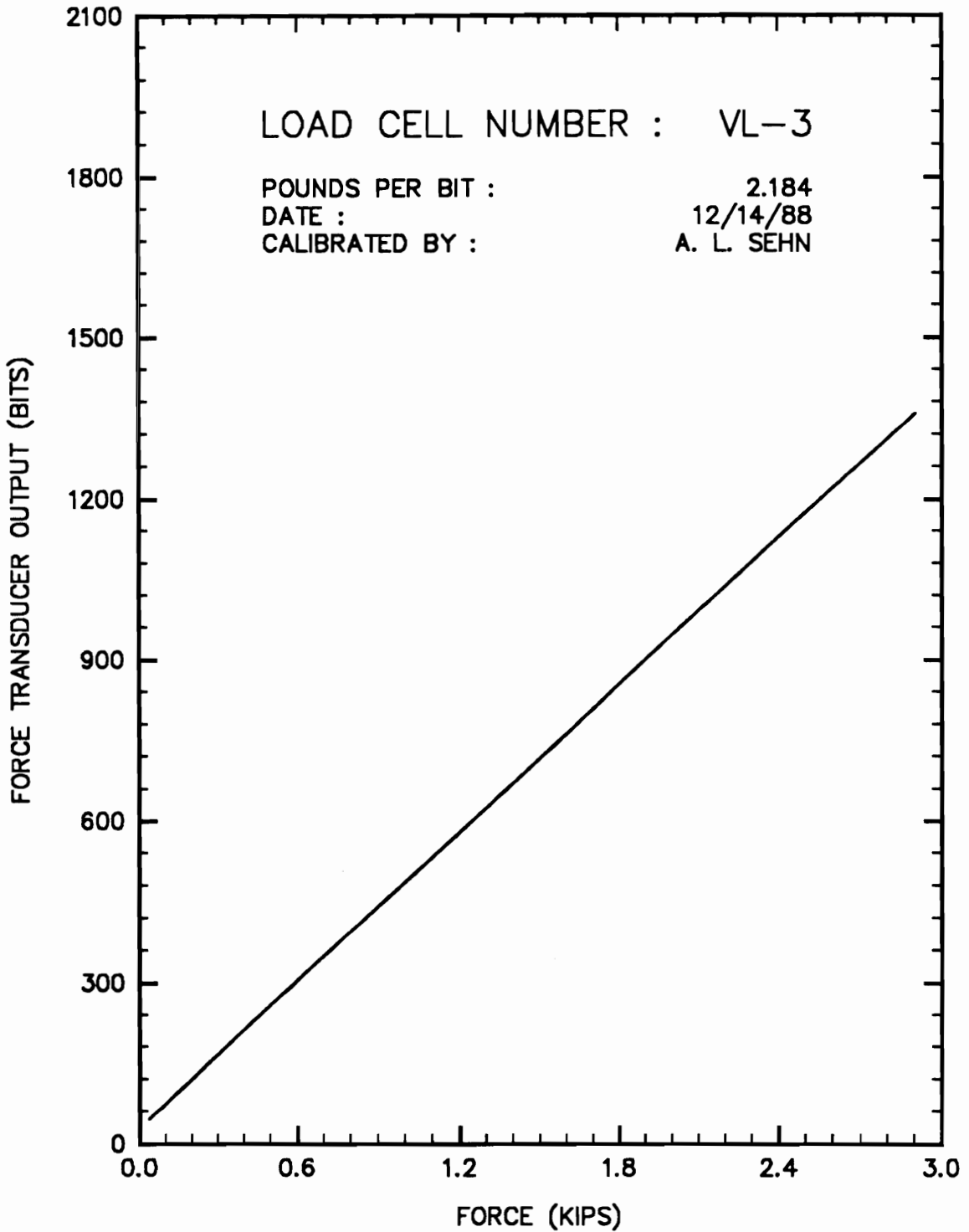


Figure 5.9) Calibration Curve for Vertical Load Cell Number VL-3.

Table 5.3) Force Transducer Calibration Factors.

Transducer Number	Calibration Factor (pounds/bit)
HL-01	8.050
HL-02	8.026
HL-03	8.058
HL-04	8.051
HL-05	8.034
HL-06	8.045
HL-07	8.055
HL-08	8.043
HL-09	8.005
HL-10	7.889
HL-11	8.076
HL-12	8.080
VL-01	2.167
VL-02	2.189
VL-03	2.184
VL-04	2.181
VL-05	2.160
VL-06	2.193
VL-07	2.177
VL-08	2.163

The cause of the underregistration is not completely understood. However, the test results are adjusted to account for the underregistration, and the calibration factors can be checked periodically to maintain the desired level of confidence in the accuracy of the test data.

5.7.2 Displacement Transducers

Each Linear Variable Differential Transformer (LVDT) was calibrated by mounting it in a frame with a micrometer and coupling the stem of the LVDT to the micrometer. Each LVDT was calibrated at the one-tenth points throughout its rated length in both the extending and the retracting directions. In accordance with the manufacturers specifications, the response of the transducers was found to be extremely repeatable but noticeably nonlinear.

The data-acquisition program uses the average reading at each of the one-tenth point calibration points and interpolates linearly between these points to determine the position of the tip of the LVDT. This approach incorporates the inherent nonlinearity of the LVDT into the data interpretation and allows an accuracy of ± 0.0005 inches to be achieved.

5.7.3 Earth Pressure Cells

The earth pressure cells were calibrated using the system shown in Figure 5.10. Uniform normal pressure was applied to the earth pressure cell by pressurizing the rubber membrane in the calibration unit. The pressure was adjusted using a precision regulator and was measured using

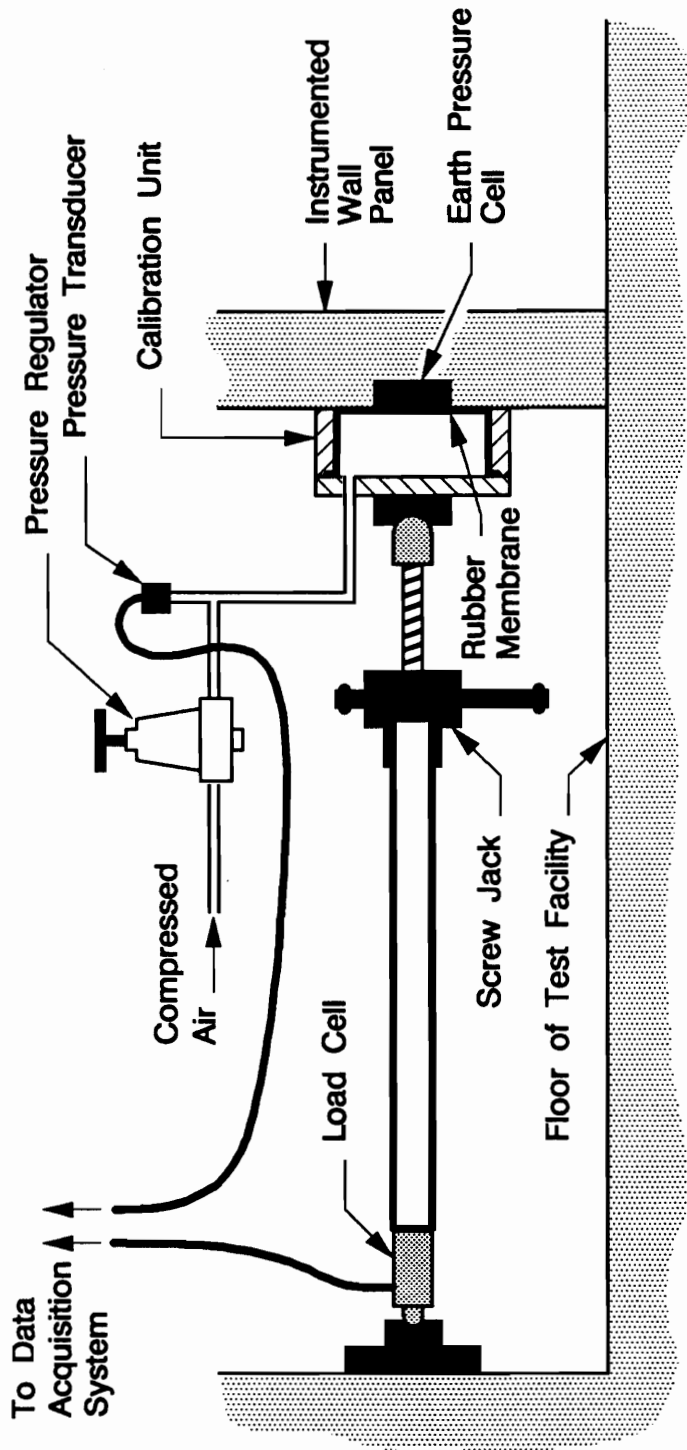


Figure 5.10) Earth Pressure Cell Calibration System.

an electrical pressure transducer. The pressure transducer was calibrated using a pressure gauge having an accuracy of ± 0.066 lb/in². The output of the pressure transducer and the earth pressure cell were recorded by the data-acquisition system.

The calibration factors for the Gloetzl cells are in bits per lb/in². The calibration plot for Gloetzl cell number 1 is shown in Figure 5.11. The linear response, with only minor hysteresis, is typical of all of the Gloetzl cells. The calibration factors for all of the earth pressure cells are reported in Table 5.4.

The calibration plots for the Carlson earth pressure cells were also linear with only minor hysteresis. The calibration factor for a Carlson cell is the ratio of the calculated pressure to the applied pressure. During a test, the actual pressure is determined by dividing the calculated pressure by the calibration factor.

The calibration plot for Geonor cell number 1 is shown in Figure 5.12. As reported by the manufacturer, the relationship between applied pressure and frequency is nonlinear over the rated pressure range. However, for the 0 to 5 lb/in² pressure range expected during this study, the response can be taken to be linear at 0.075 lb/in² per Hz. One of the two Geonor cells became inoperative during start-up and has not been used.

5.7.4 Temperature Sensors

The copper-constantan thermocouples of the type used in the Retaining Wall Facility are quite common. They have been standardized

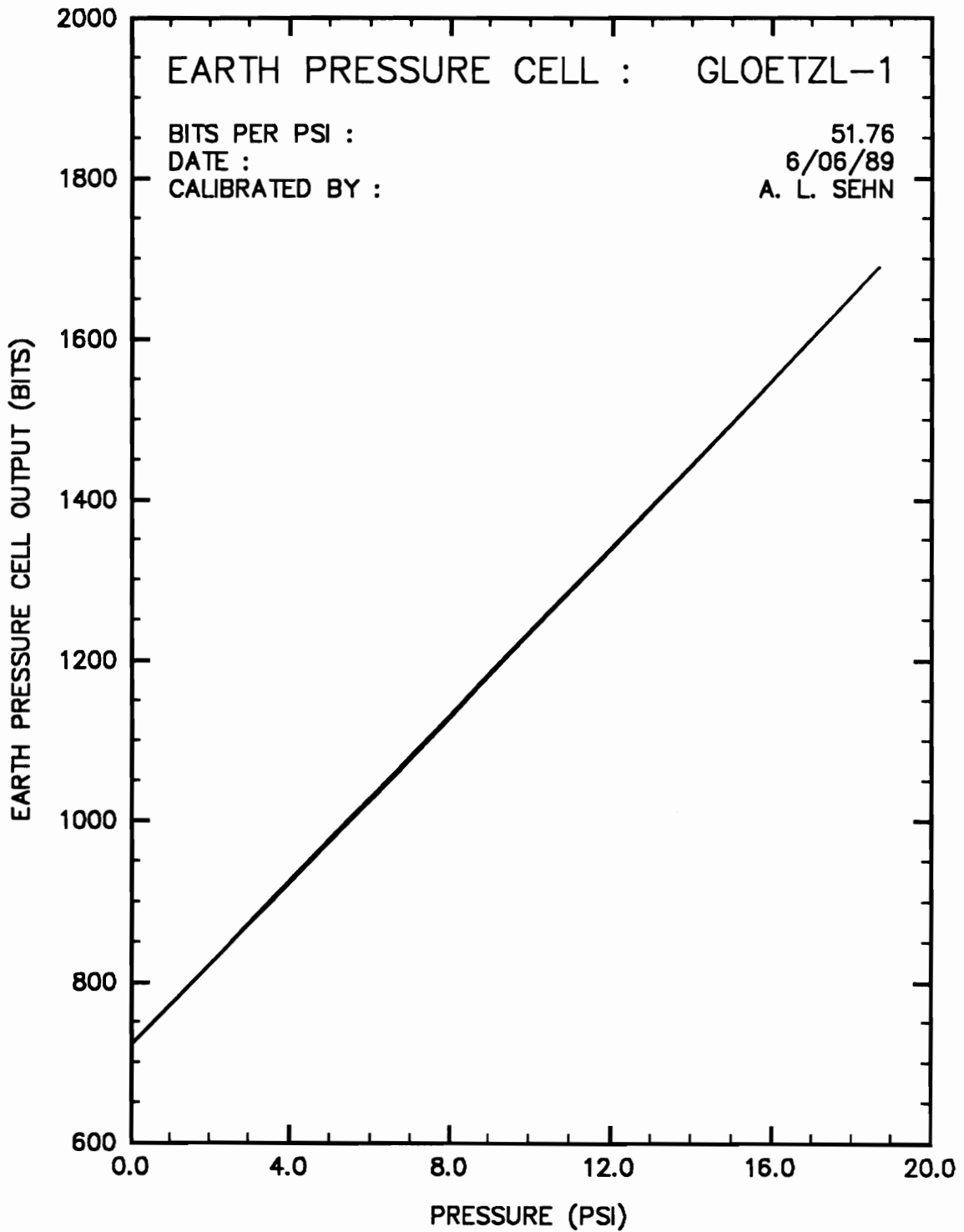


Figure 5.11) Calibration Curve for Gloetzl Earth Pressure Cell Number 1.

Table 5.4) Earth Pressure Cell Calibration Factors.

Earth Pressure Cell Number	Calibration Factor
Gloetzl-01	51.76 bits/(lb/in ²)
Gloetzl-02	51.82 bits/(lb/in ²)
Gloetzl-03	51.72 bits/(lb/in ²)
Gloetzl-04	51.83 bits/(lb/in ²)
Gloetzl-05	51.37 bits/(lb/in ²)
Gloetzl-06	52.57 bits/(lb/in ²)
Gloetzl-07	52.11 bits/(lb/in ²)
Gloetzl-08	52.25 bits/(lb/in ²)
Gloetzl-09	50.31 bits/(lb/in ²)
Gloetzl-10	52.30 bits/(lb/in ²)
Gloetzl-11	51.86 bits/(lb/in ²)
Carlson-1	0.975 (calculated/applied)
Carlson-2	0.994 (calculated/applied)
Carlson-3	0.877 (calculated/applied)
Carlson-4	0.980 (calculated/applied)
Geonor-1	0.075 (lbs/in ²)/Hz [*]
Geonor-2	inoperative before calibration

* approximately linear from 0 to 5 lbs/in²

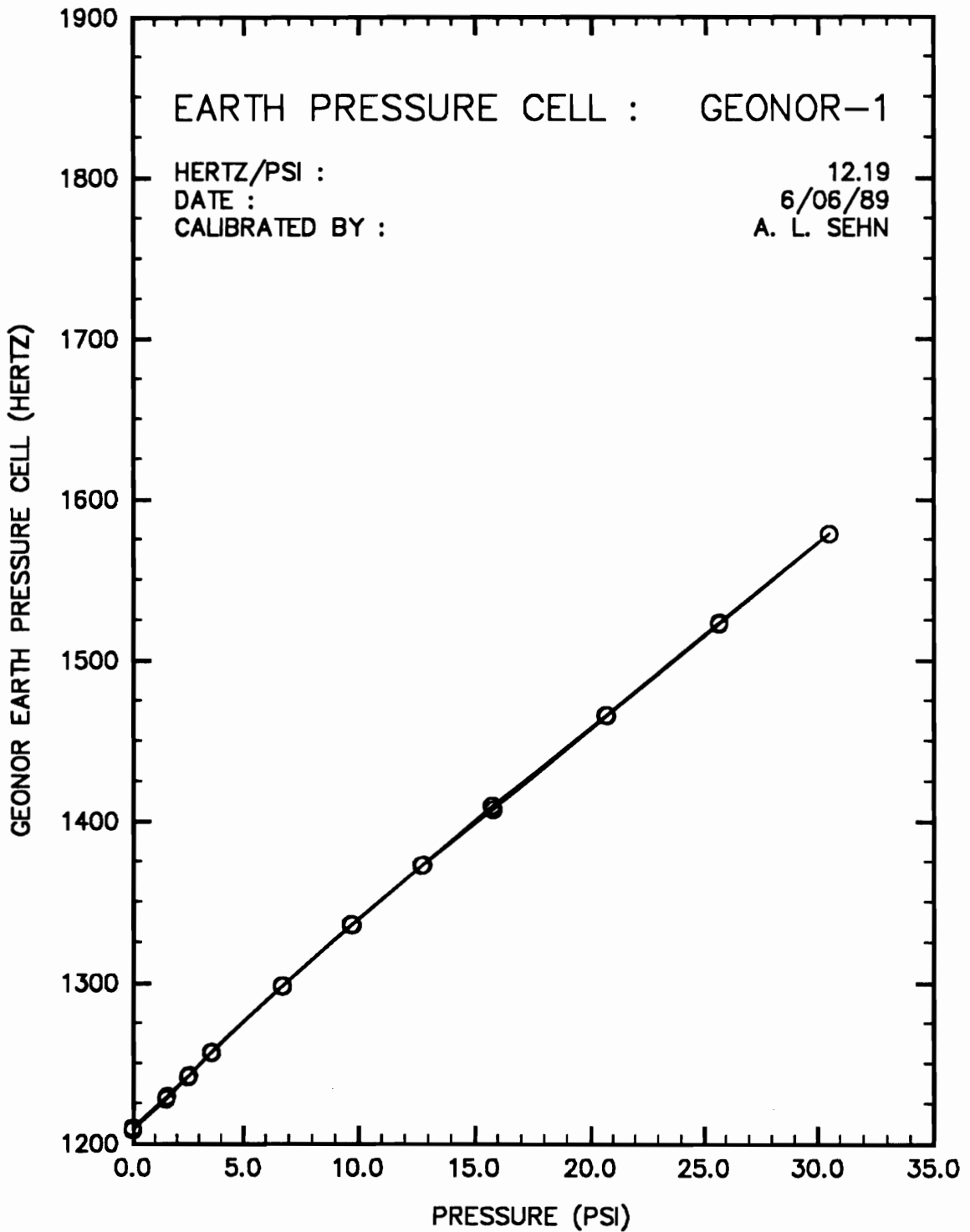


Figure 5.12) Calibration Curve for Geonor Earth Pressure Cell Number 1.

to the point that their performance can be accurately represented by a seventh-degree polynomial relating temperature to the electromotive force of the thermocouple. The coefficients for the polynomial equation are published in many textbooks on instrumentation and in temperature measurement handbooks.

The thermocouples were not calibrated, but the performance of the overall thermocouple/data-acquisition system was evaluated by comparing the temperatures indicated by the thermocouples to those measured using a mercury thermometer and by using a distilled water ice bath as a 32.0° F reference point. The accuracy of the temperature measuring system was determined to be about $\pm 0.5^\circ$ F.

5.7.5 Distance Transducers

As discussed earlier, the distance indicated by a UDMD measurement is based on the speed of sound in air. The speed of sound in air is a function of temperature and humidity. In order for the UDMDs to measure distance accurately, it is necessary to determine the speed of sound for the atmospheric conditions at the time of measurement. To accomplish this, a UDMD was installed to measure the distance to a fixed target. This measurement provides a calibration reading each time a set of measurements is made, and results in an accuracy of ± 0.1 inches in the measured fill depths.

5.8 ACCURACY OF INSTRUMENTS

The estimated accuracies of the instruments are listed in Table 5.5.

Table 5.5) Estimated Instrument Accuracies.

Instrument	Estimated Accuracy*
Gloetzl Cells	± 0.25 psi
Carlson Cells	± 0.50 psi
Geonor Cells	± 0.25 psi
Horizontal Load Cells	± 50 lbs
Vertical Load Cells	± 15 lbs
Ultrasonic Distance Measuring Devices	± 0.10 in.
LVDTs	± 0.0005 in.
Thermocouples	± 0.5 Deg. F

* These values were estimate based on consideration of overall system performance as installed in the Instrumented Retaining Wall Facility at Virginia Tech and may not represent the accuracy of the instrument alone or under different conditions.

These values reflect the influence of all of the factors that determine the repeatability of measurements over a period as long as the several days involved in a test, as well as the intrinsic accuracy of the instruments. The estimates also take into account the use of multiple readings to improve the resolution of each set of readings.

5.9 COSTS

Approximate costs for the components of the Instrumented Retaining Wall facility are listed in Table 5.6. The total is about \$173,000. It is interesting to compare the cost of this facility with the cost of a similar facility built by Terzaghi at MIT in about 1930. Terzaghi (1932) stated that the total investment in the MIT facility was about \$50,000. Based on the change in the Engineering News Record Construction Cost Index, the comparable current cost would be about \$1,200,000 in 1990. The difference in cost is largely attributable to the availability of smaller and less costly devices for measuring the forces on the wall. Terzaghi's facility had intricate and elaborate force-measuring systems based on the principle of balance beam scales. The Instrumented Retaining Wall Facility at Virginia Tech uses electrical measuring devices which are more compact and less expensive.

The cost of operation of the new facility is probably also much lower, due to the fact that power equipment greatly reduces the amount of time required for material handling, automatic data acquisition reduces the time for collecting data, and computer programs reduce the time required for processing and plotting the information.

Table 5.6) Approximate Cost of Instrumented Retaining Wall Facility.

Reinforced Concrete Sidewalls, Floor, and Ramp	\$15,500
Gloetzl earth pressure cells and transducers (11)	5,300
Carlson earth pressure cells (4)	3,100
Geonor earth pressure cells (2)	1,500
Jacks to move walls (4)	2,500
Horizontal load cells (materials + labor for 12)	8,400
Vertical load cells (materials + labor for 8)	8,000
Ultrasonic Distance Measuring Devices (16, not all deployed)	3,500
LVDTs (9)	4,100
Thermocouples (5)	200
Video camera, VCR, TV and controller	1,400
Analog to Digital card DASH-8 (1)	400
Frequency to Digital card CTM-05 (1)	300
Multiplexing cards EXP-16 (7)	2,600
Computer IBM XT (1)	1,500
Bobcat Loader	11,000
Wacker BPU 2440A Compactor	3,000
Santo SV-104 Compactor	1,400
Wacker BS 60Y Compactor	1,900
Rototiller	600
Soil delivery & conditioning	4,000
Building & crane (half of 2400 ft2 bldg)	45,000
Miscellaneous materials	5,000
Design	25,000
Fabrication	6,000
Assembly	10,000
Calibration	2,000
Total:	\$173,200

CHAPTER 6

TEST PROGRAM AND DATA EVALUATION

6.1 INTRODUCTION

The Instrumented Retaining Wall Facility at Virginia Tech was used to investigate the lateral earth pressures and vertical shear forces exerted on stiff retaining structures by compacted backfill. Four tests were performed. The wall was backfilled with Yatesville silty sand. The following sections describe the backfill material and test procedure, and discuss the test results.

6.2 SOIL DESCRIPTION

The backfill material is a silty sand from the foundation of Yatesville Dam in Kentucky. Before use in the Instrumented Retaining Wall Facility, the material was sieved using a commercial-grade wire mesh with openings of about 0.20 inches, and the oversized portion was discarded. Gradation curves for the backfill material, shown in Figure 6.1, indicate that about 46 to 48 percent of the material passes the #200 sieve. The material is non-plastic according to ASTM D-4318 and classifies as a silty sand (SM) according to the Unified Classification System, as defined by ASTM D-2487. The specific gravity of the soil solids is 2.66, based on the ASTM D-854 test method.

The relationships between compacted dry density and water content are shown in Figure 6.2 for the standard Proctor (ASTM D-698) and

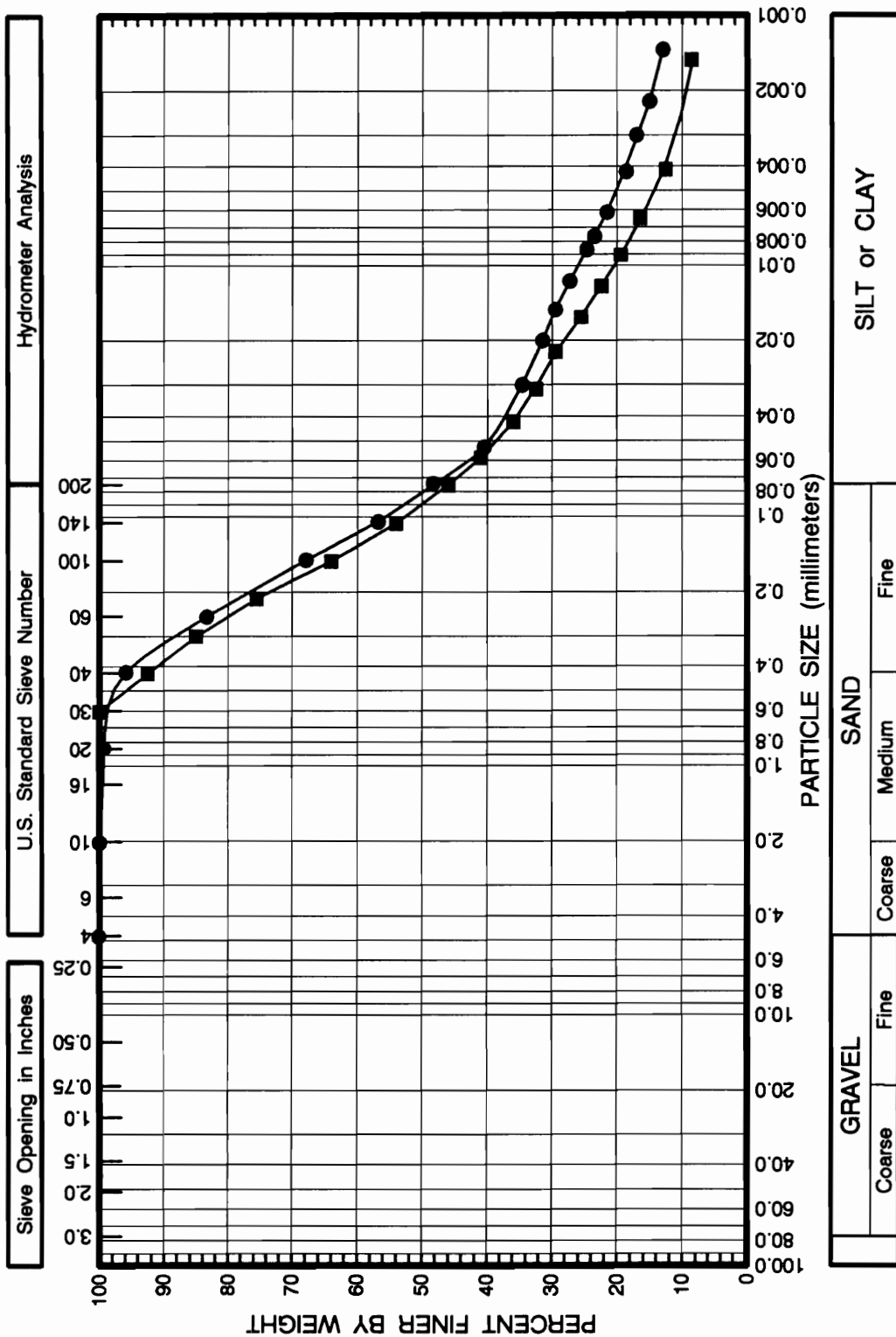


Figure 6.1) Grain Size Distribution of Yatesville Silty Sand.

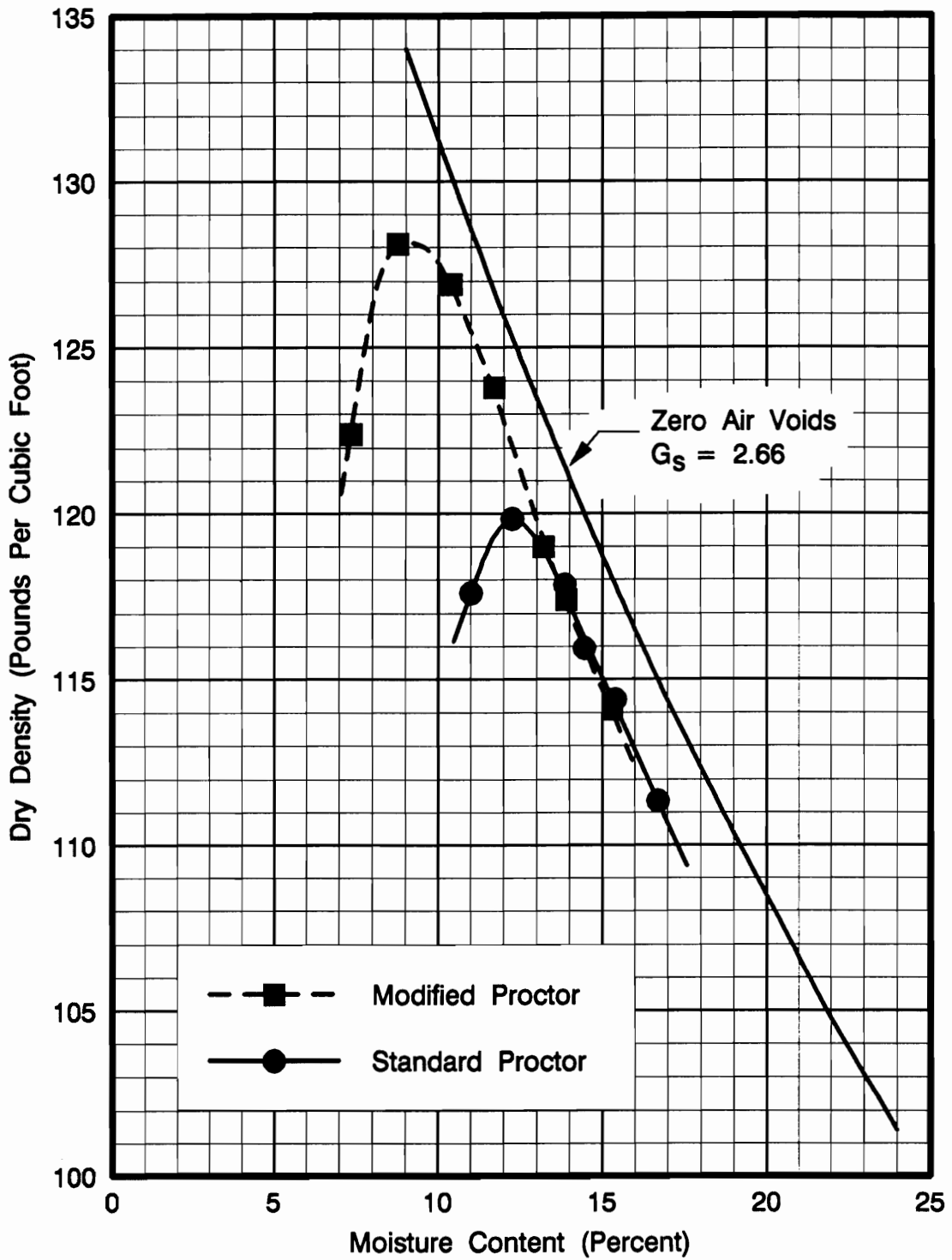


Figure 6.2) Moisture Density Relationship for Yatesville Silty Sand.

modified Proctor (ASTM D-1557) compaction efforts. For the standard effort, the maximum dry density is 120.0 lb/ft³ and the optimum water content is 12.5 percent. For the modified effort, the maximum dry density is 128.0 lb/ft³ and the optimum water content is 9.0 percent. The values of relative compaction used in this study are calculated with reference to the maximum dry density for the standard compactive effort.

The strength parameters of the compacted backfill were investigated using unconsolidated undrained (UU) triaxial tests. Samples for strength testing were obtained from each of the four tests. The samples were obtained with a small trailer mounted drill rig using three-inch-diameter thin-walled Shelby tubes.

A total of twenty-two UU tests were performed. Table 6.1 summarizes the test conditions, specimen conditions, and failure stresses for the UU tests. The stress-strain graphs are contained in Appendix D.

UU tests on specimens from tests EP-1 and EP-2 can be grouped together because these two tests were very similar with respect to test procedure and moisture content and dry unit weight of the compacted fill. The results of sixteen UU tests on specimens from tests EP-1 and EP-2 are shown in Figure 6.3 in terms of shear stress at failure (q) versus average principal stress (p). The shear stress at failure was taken as the maximum shear stress during the test, if it occurred at an axial strain less than ten percent. Otherwise, the shear stress corresponding to ten percent axial strain was taken as the shear stress at failure. From Figure 6.3, the total stress strength parameters for

Table 6.1) Summary of Unconsolidated Undrained Triaxial Tests on Samples of Compacted Yatesville Silty Sand.

Test No.	Shelby Tube No.	Dia. (in.)	Cell Press (psi)	$(\sigma_1 - \sigma_3)_f$ (psi)	q (psi)	p (psi)	w (%)	γ_d (pcf)	S (%)
EP-1	2	2.8	0.0	22.6	11.30	11.30	14.3	115.0	85
EP-1	2	2.8	2.0	25.7	12.85	14.85	14.3	115.5	86
EP-1	4	2.8	4.0	28.5	14.25	18.25	14.4	116.7	89
EP-1	4	2.8	5.0	29.9	14.95	19.95	14.0	114.8	82
EP-2	1	2.8	0.0	20.6	10.30	10.30	13.7	115.2	77
EP-2	1	2.8	2.0	31.0	15.50	17.50	13.6	115.9	84
EP-2	1	2.8	3.0	23.3	11.65	14.65	13.7	115.3	81
EP-2	3	2.8	5.0	28.6	14.30	19.30	13.7	115.1	82
EP-2	2	1.4	1.1	26.0	13.00	14.10	13.0	117.0	82
EP-2	2	1.4	1.1	31.0	15.50	16.60	11.9	114.4	70
EP-2	2	1.4	3.0	22.3	11.15	14.15	13.6	115.4	81
EP-2	2	1.4	5.0	27.9	13.95	18.95	12.9	114.4	76
EP-3	2	2.8	0.0	6.3	3.15	3.15	13.2	108.2	65
EP-3	3	2.8	2.0	14.5	7.25	9.25	13.0	110.8	66
EP-3	4	2.8	3.0	22.8	11.40	14.40	13.7	112.0	74
EP-3	4	2.8	5.0	20.8	10.40	15.40	13.4	111.9	67
EP-3	4	2.8	5.0	20.0	10.00	15.00	13.4	110.6	67
EP-4	3	2.8	0.0	8.0	4.00	4.00	9.6	94.1	33
EP-4	4	2.8	2.0	12.9	6.45	8.45	9.8	101.2	40
EP-4	2	2.8	3.0	13.4	6.70	9.70	9.9	102.0	42
EP-4	2	2.8	5.0	16.6	8.30	13.30	10.0	100.3	40
EP-4	3	2.8	5.0	17.7	8.85	13.85	9.6	100.9	39

$(\sigma_1 - \sigma_3)_f$ = principal stress difference at failure

q = 0.5 $(\sigma_1 - \sigma_3)_f$

p = 0.5 $(\sigma_1 + \sigma_3)_f$

w = water content

γ_d = dry unit weight

S = degree of saturation

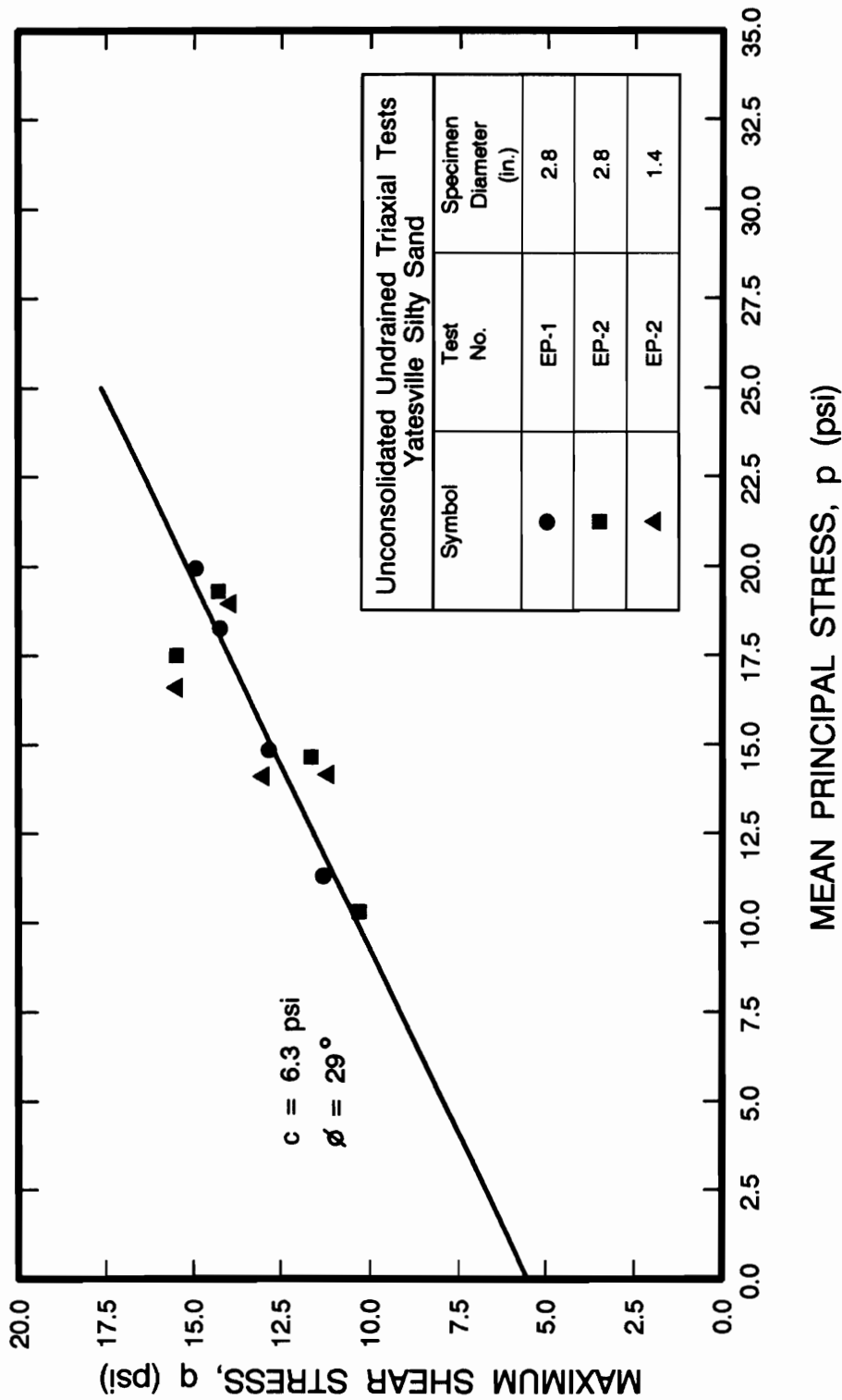


Figure 6.3) Results of Unconsolidated Undrained Triaxial Tests on Samples of Compacted Yatesville Silty Sand from Tests EP-1 and EP-2.

the backfill in tests EP-1 and EP-2 can be represented by a total stress friction angle of $\phi = 29^\circ$ and a cohesion of $c = 6.3 \text{ lb/in}^2$.

The results of UU tests on samples from tests EP-3 and EP-4 are shown in Figures 6.4 and 6.5, respectively. The shear stress at failure was interpreted as described above. From the information in Figure 6.4, the total stress strength parameters for the backfill of test EP-3 can be taken as $\phi = 34^\circ$ and $c = 2.1 \text{ lb/in}^2$. For the backfill of test EP-4, the strength parameters are $\phi = 28^\circ$ and $c = 2.5 \text{ lb/in}^2$, based on Figure 6.5.

6.3 TEST PROCEDURE

Before the first backfilling, the backfill material was moisture conditioned and thoroughly mixed to produce a uniform moisture content about 2 percent higher than the optimum moisture content for the standard Proctor compaction effort. The stockpiled backfill material was covered with a plastic sheet between tests, and as much as possible during backfilling, to prevent drying. The stockpile area is located indoor and adjacent to the Retaining Wall Facility.

During the backfilling operation, a Bobcat 643 skid-steer loader is used to move soil from the stockpile into the backfill area. As the material is being loaded from the stockpile area, each bucket of material is repeatedly spread into a thin layer and reloaded until all soil lumps are smaller than about three inches. The material is then hauled to the Instrumented Retaining Wall Facility, placed on top of the backfill, and leveled by hand.

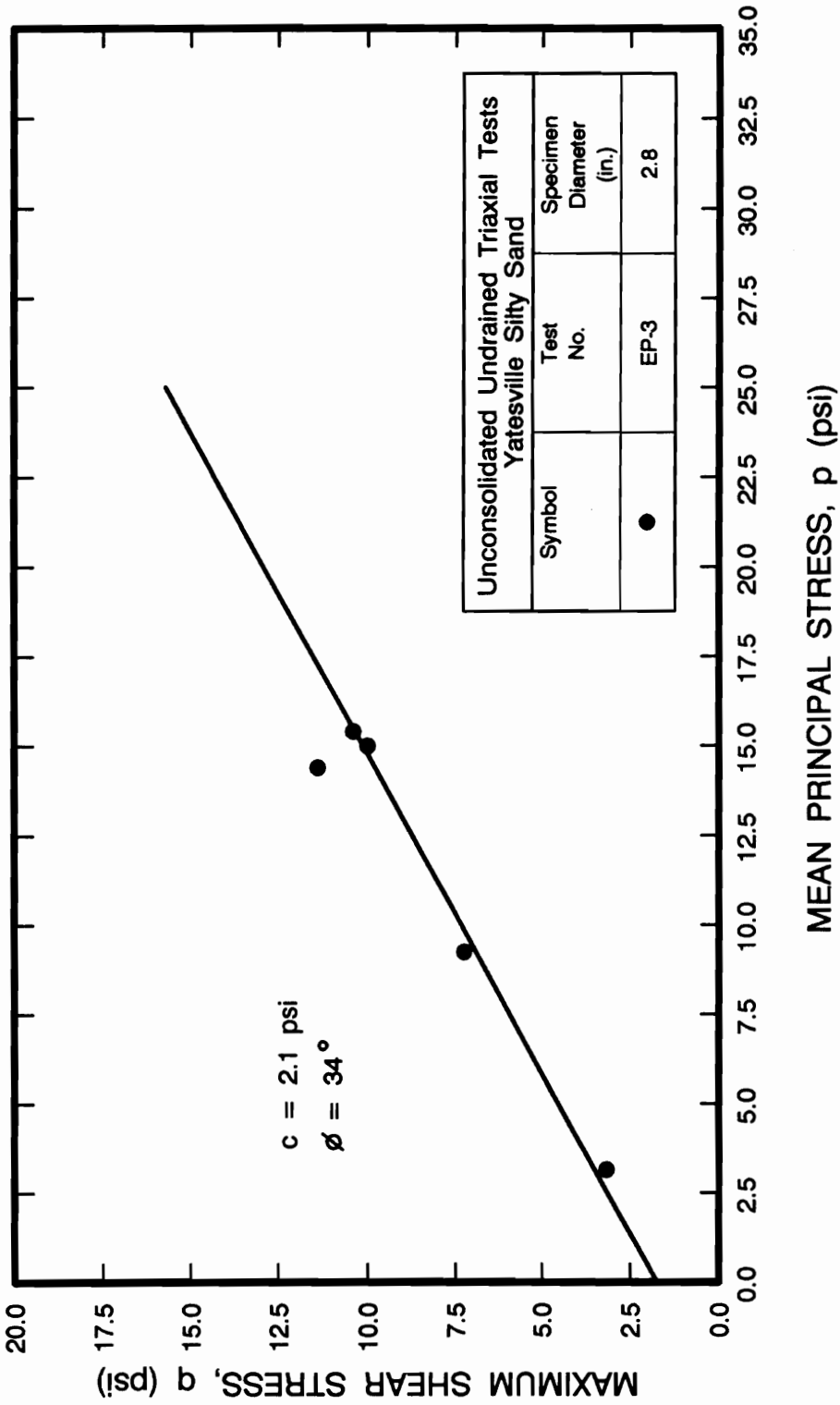


Figure 6.4) Results of Unconsolidated Undrained Triaxial Tests on Samples of Compacted Yatesville Silty Sand from Test EP-3.

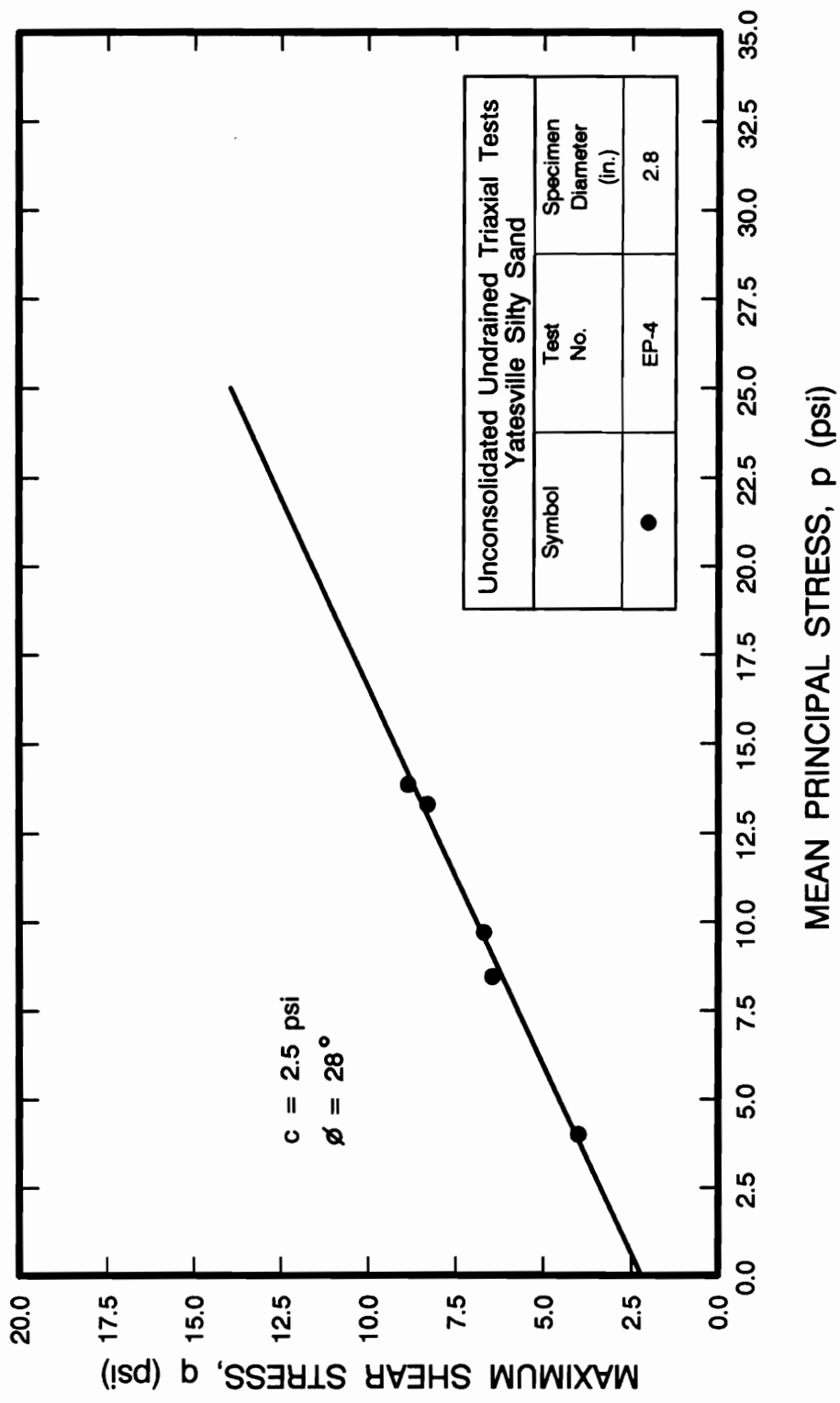


Figure 6.5) Results of Unconsolidated Undrained Triaxial Tests on Samples of Compacted Yatesville Silty Sand from Test EP-4.

The backfill is placed in layers of a thickness that will, on average, produce the desired compacted layer thickness. The compacted layer thickness used for tests EP-1 and EP-2 was 4 inches and the thickness used for tests EP-3 and EP-4 was 6 inches.

Each layer was compacted by 5 passes of a Wacker BPU 2440 A vibratory plate compactor. The time required to compact each layer was recorded. The total compactor time for each test is listed in Table 6.2 along with other test characteristics.

During each test, a microcomputer-based data-acquisition system is used to record each of the instruments before the compaction of each lift and again after each lift has been compacted. The information is stored by the computer for later retrieval and interpretation.

6.4 TEST RESULTS

The results of the first four tests in the Instrumented Retaining Wall Facility are presented in the following sections. The primary factors that were varied during this series of tests are the water content and compacted lift thickness of the backfill. For reference, these two items are listed on each of the graphs used to present the test results.

6.4.1 Measured Wall Displacements

Wall displacements are measured at two points on the vertical centerline of each panel. One point is six inches above the base of the wall, and the other point is seventy-five inches above the base. The

Table 6.2) Summary of Earth Pressure Test Characteristics.

Test Number	Compacted Lift Thickness (inches)	Average Dry Density (lb/ft ³)	Average Water Content (percent)	Total Compactor Time (minutes)	Elapsed Time Start to Finish (hours)
EP-1	4	120	14.5	173	28.5*
EP-2	4	119	14.2	173	13.0
EP-3	6	120	13.7	112	8.8
EP-4	6	106	10.1	89	8.5

* Includes a 12.5 hour intermission.

measured wall displacements for the four tests are shown, as a function of fill depth, in the lower parts of Figures 6.6 through 6.9. The upper parts of these figures show, as a function of fill depth, the average horizontal forces per foot of wall measured by the upper and lower horizontal force transducers and the average total horizontal force per foot of wall.

The relationships between the average horizontal force, the fill depth, and the wall displacements are similar for all four tests. During the early stages of backfilling the resultant earth pressure force is below the lower horizontal force transducer. As a result, the upper horizontal force transducer experiences a negative force and the upper displacement transducer registers movement toward the backfill. The lower displacement transducer, which is below the lower horizontal force transducer, registers movement away from the backfill. As the fill depth increases, the magnitude of the horizontal force resultant increases, and its point of application moves higher on the wall. After the location of the resultant force raises above the lower load cells, the forces in the upper load cells tend toward compression and the movements registered by the upper displacement transducers indicate relative movements away from the backfill.

The only exceptions to the similarity among these graphs are seen in Figure 6.6, where there are abrupt changes in the measured wall displacements and horizontal forces at a fill depth of about 3.8 feet. The backfilling of test EP-1 was performed over a two-day period with an intermission of about 12.5 hours at a fill depth of about 3.8 feet. The

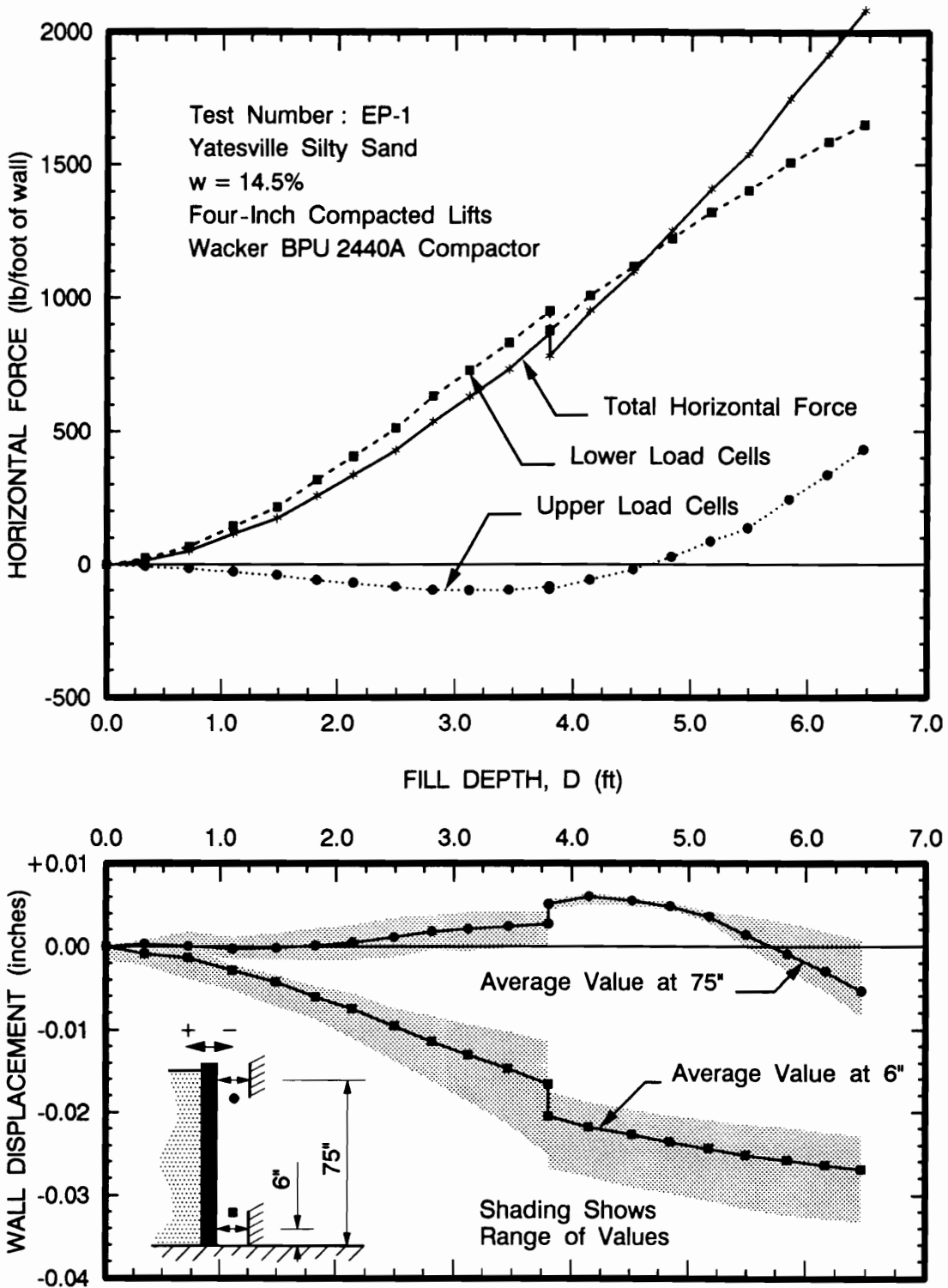


Figure 6.6) Measured Horizontal Forces and Wall Displacements as Functions of Fill Depth for Test EP-1.

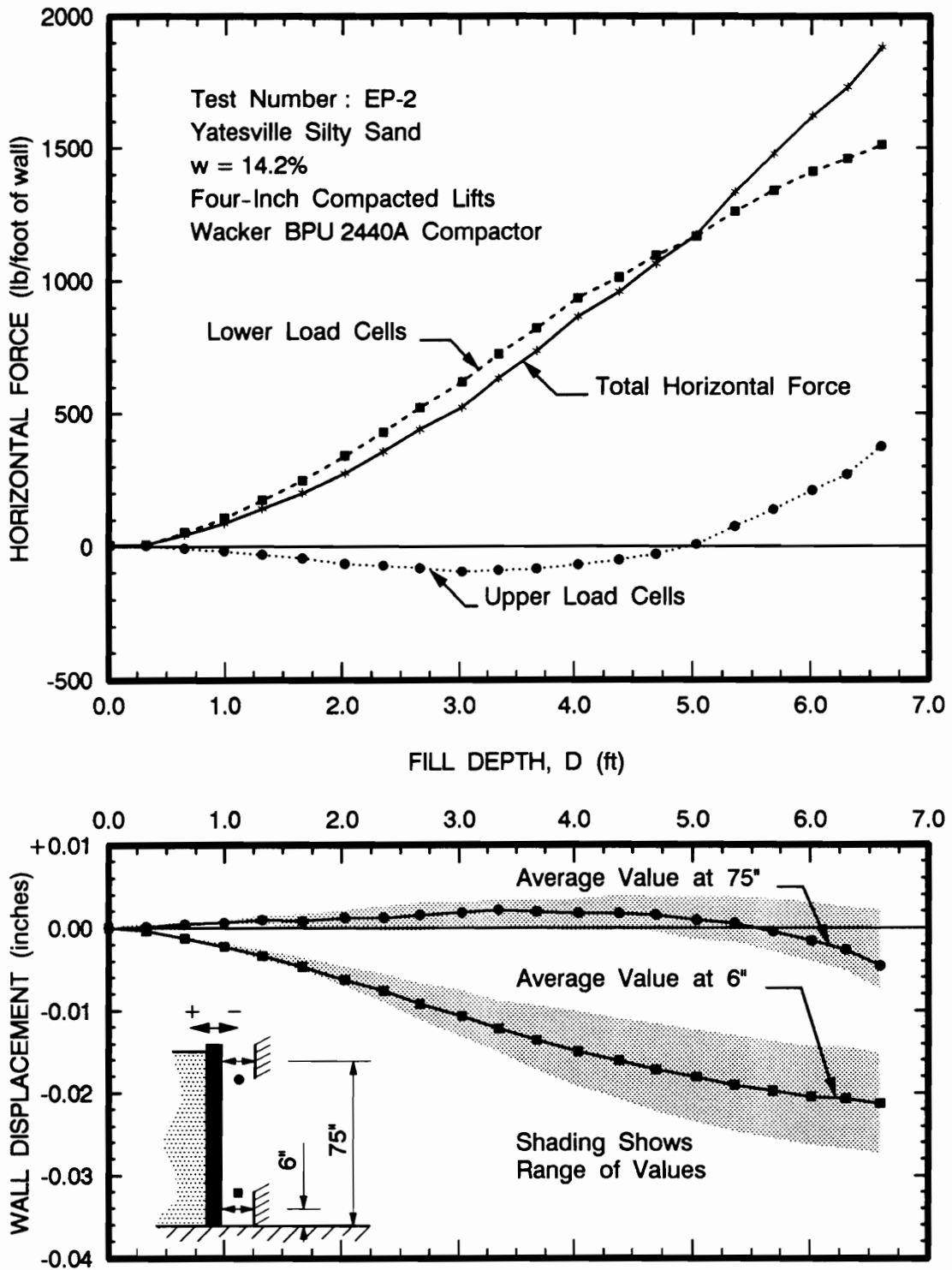


Figure 6.7) Measured Horizontal Forces and Wall Displacements as Functions of Fill Depth for Test EP-2.

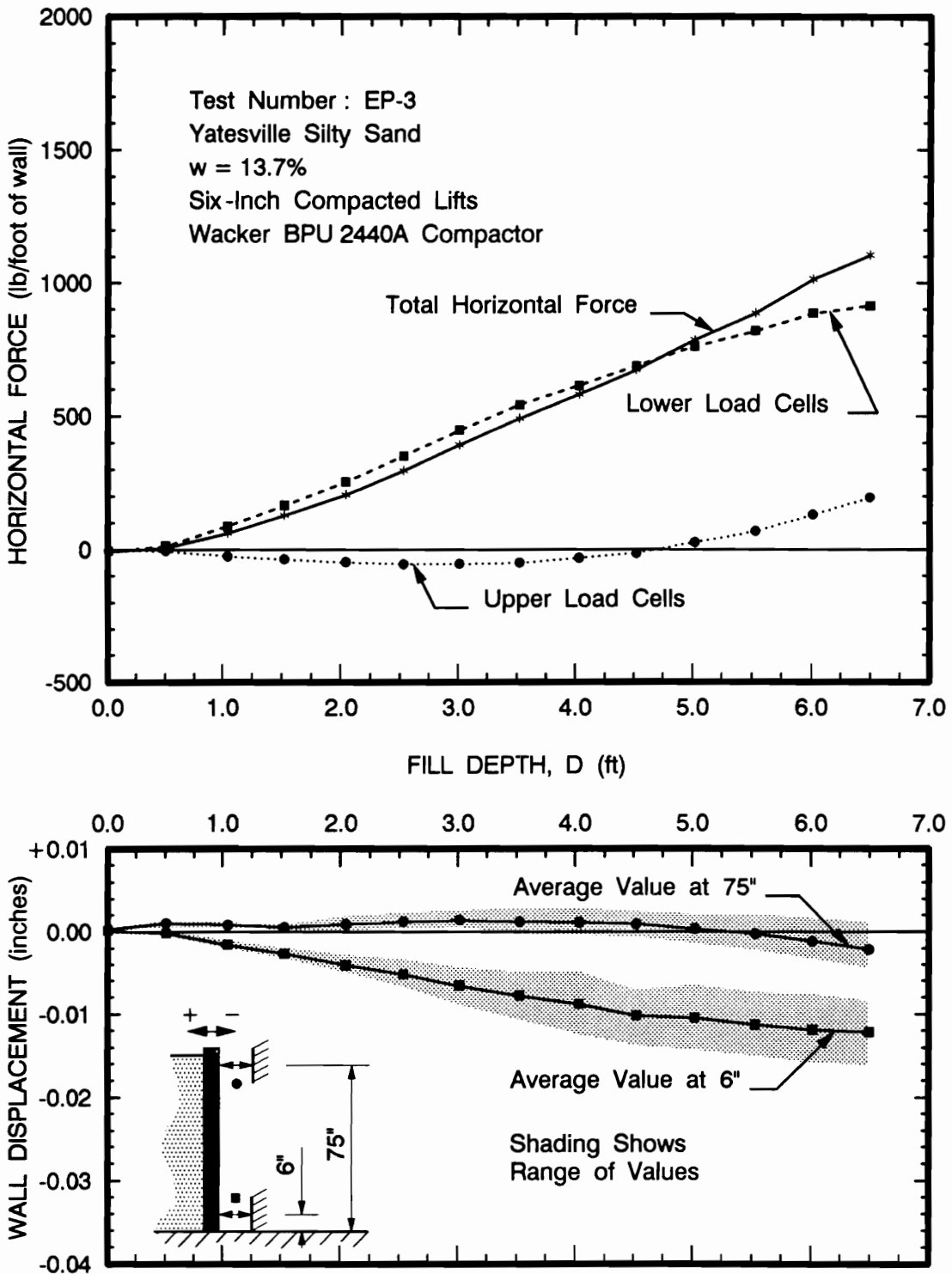


Figure 6.8) Measured Horizontal Forces and Wall Displacements as Functions of Fill Depth for Test EP-3.

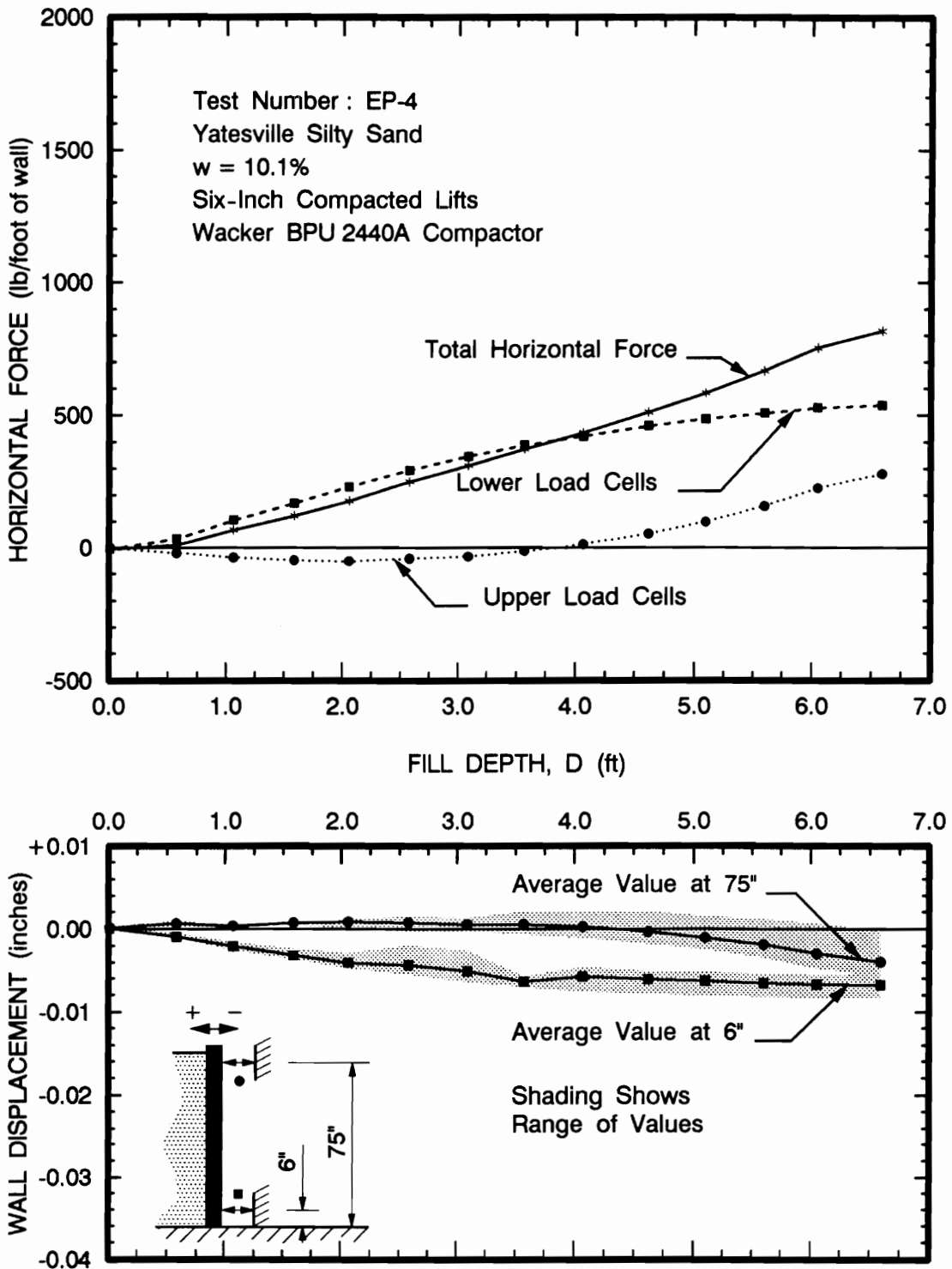


Figure 6.9) Measured Horizontal Forces and Wall Displacements as Functions of Fill Depth for Test EP-4.

abrupt changes seen in Figure 6.6 represent the changes that occurred during the 12.5 hour intermission. Tests EP-2 through EP-4 were conducted in one continuous effort without delays.

The average displacements measured near the top of the wall, at the end of construction, ranged from 0.002 inches for test EP-3 to 0.0055 inch for test EP-1. Near the bottom of the wall, the average movements at the end of construction ranged from 0.007 inch for test EP-4 to 0.027 inch for test EP-1. The data for all four tests indicated that, at the end of construction, the wall had moved away from the backfill and the movement was greater near the bottom of the wall than near the top. The amount of wall displacement is related to the magnitude of the horizontal force; in general, at the end of construction, the largest displacements correspond with the largest loads and the smallest displacements correspond with the smallest loads.

Terzaghi (1934a) found that, for compacted backfill, a wall movement of $\Delta/H = 0.001$, where Δ is the wall movement measured at mid-height and H is the height of the wall, was sufficient to reduce the lateral earth pressure to its minimum value. The maximum wall movements measured during the four earth pressure tests were those measured at the end of construction for test EP-1, where Δ/H was 0.00021. This value is about 20% of the value reported by Terzaghi as being required to minimize the lateral earth pressure for a compacted backfill. The other three tests showed smaller displacements, with the end of construction displacement being smallest for test number EP-4. For this test, the displacement

corresponds to $\Delta/H = 0.00007$, or about 7% of the value reported by Terzaghi.

In addition to the wall displacements being small compared to those generally accepted as being required to produce the active pressure condition, the nature of the problem being studied somewhat reduces the need for a very rigid wall system in order to obtain accurate earth pressure measurements. The process of compacting a layer of soil using multiple passes of a compaction plant allows the lateral earth pressure to be considered as a following load, particularly in the upper portion of the fill. As the soil is compacted, the lateral pressure on the wall increases. This increase in lateral pressure produces deflection of the wall that will tend to reduce the lateral earth pressures. At shallow depths, additional compaction will replace the lateral pressure that was lost due to the small wall displacements during earlier compaction. Therefore, at shallow depths, the after-compaction lateral earth pressures are not appreciably affected by small wall deformations. This reasoning has been successfully incorporated into a finite element analytical procedure by Seed and Duncan (1986) to evaluate compaction-induced stresses and deformations.

Based on the relatively small measured displacements, compared to those reported by Terzaghi (1934b) as producing the minimum value of the lateral earth pressure, and the above discussion of compaction-induced earth pressures, the Instrumented Retaining Wall Facility appears to be well suited for the experimental investigation of compaction-induced earth pressures.

6.4.2 Measured Horizontal Forces

The horizontal forces required for equilibrium of each wall panel were monitored by three horizontal force transducers. Two of the force transducers are located twenty inches above the base of the wall and one is located 60 inches above the base. The transducers for each panel are positioned symmetrically with respect to the vertical centerline of the panel.

The horizontal forces measured during the backfilling of the four tests are shown in Figures 6.10 through 6.13. The horizontal force for each panel, in pounds per linear foot of wall, is shown as a function of depth. As with the displacement measurements, there is a definite similarity in the shapes and relative positions of the curves of the four tests. The primary irregularity, seen in Figure 6.10 for test EP-1, is due to the overnight intermission of that test. The most significant observations from these figures are:

- 1) There are large variations between the forces on the four panels with the force on Panel 1 generally about one-half of that on Panel 4.
- 2) Panel 1 experiences the smallest horizontal force of the four panels for all tests.
- 3) The horizontal force on Panel 4 is larger than the force on the other panels for tests EP-2 through EP-4, and for test EP-1, is only slightly exceeded by the force on Panel 3.
- 4) In general, there is a progression of the amount of force experienced by Panels 1 through 4 with the smallest force on Panel 1 and the largest force on Panel 4.

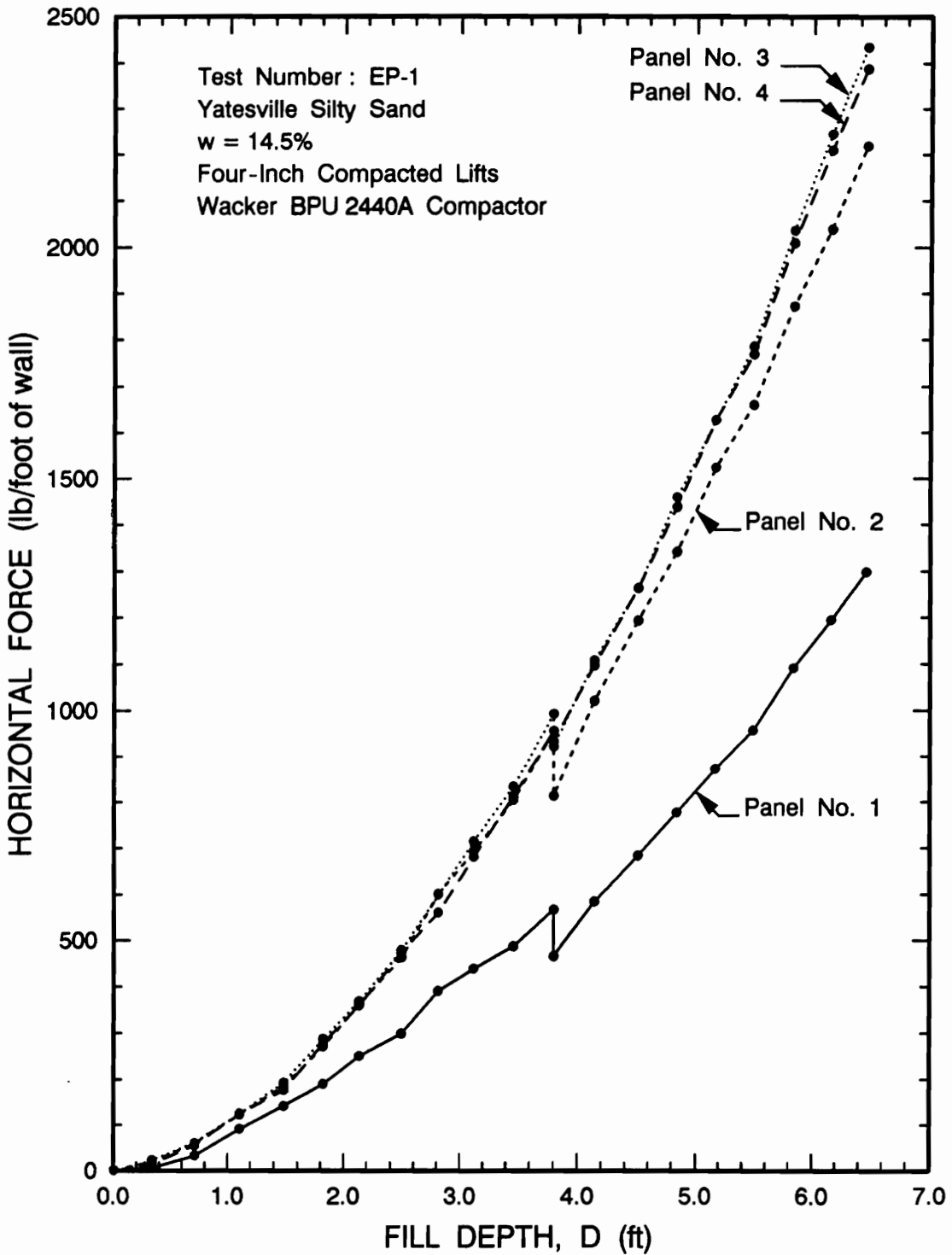


Figure 6.10) Measured Horizontal Force for each Wall Panel as a Function of Fill Depth for Test EP-1.

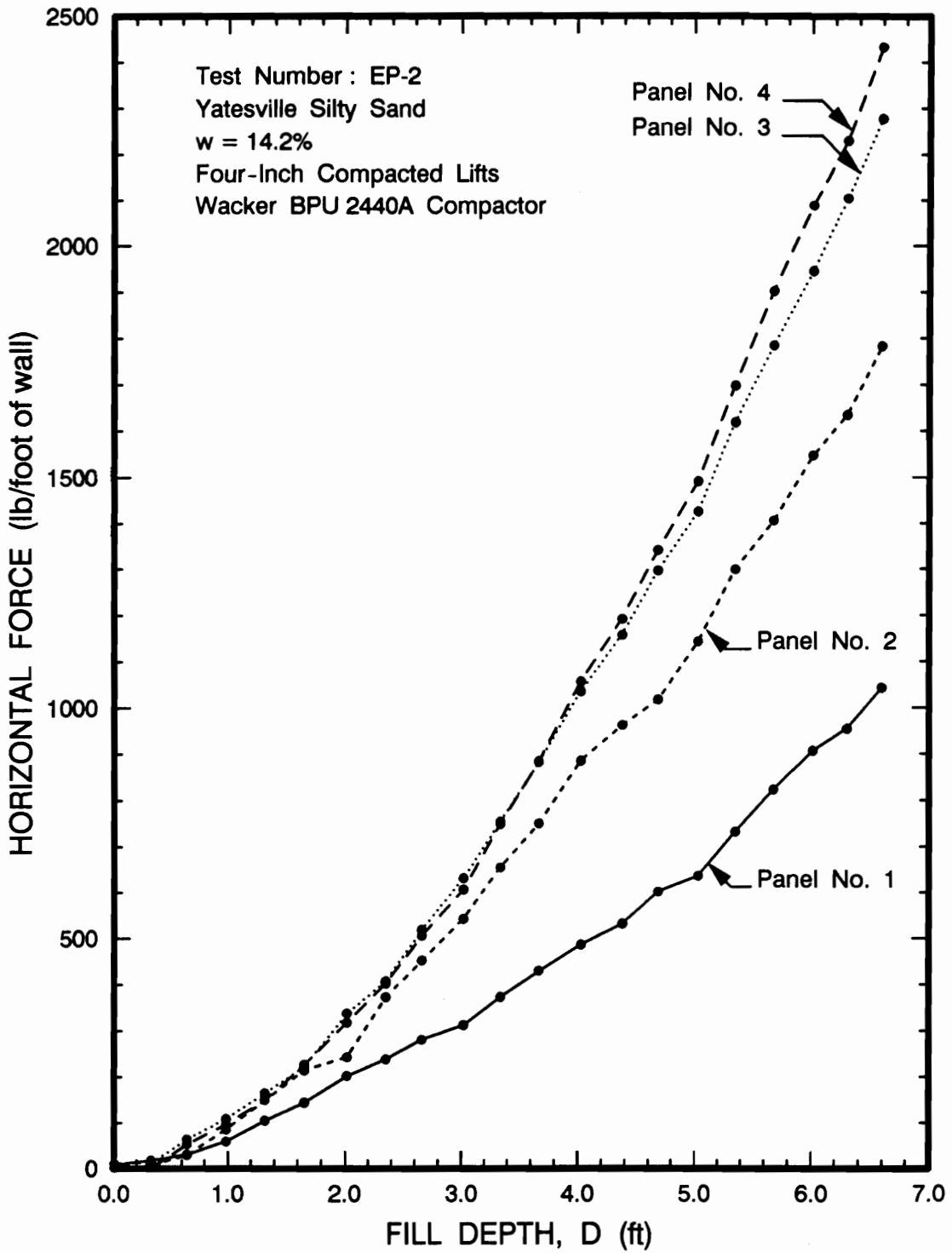


Figure 6.11) Measured Horizontal Force for each Wall Panel as a Function of Fill Depth for Test EP-2.

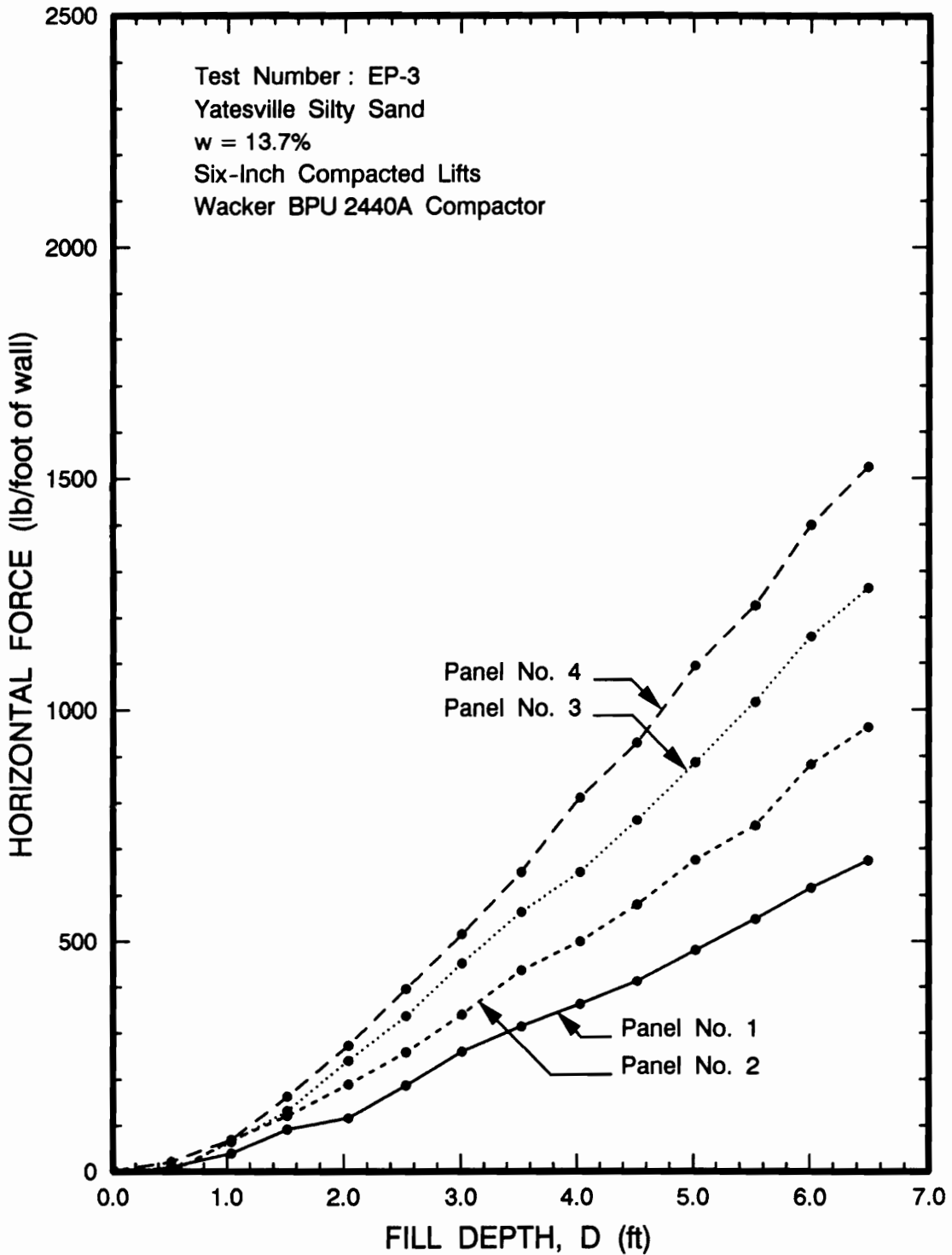


Figure 6.12) Measured Horizontal Force for each Wall Panel as a Function of Fill Depth for Test EP-3.

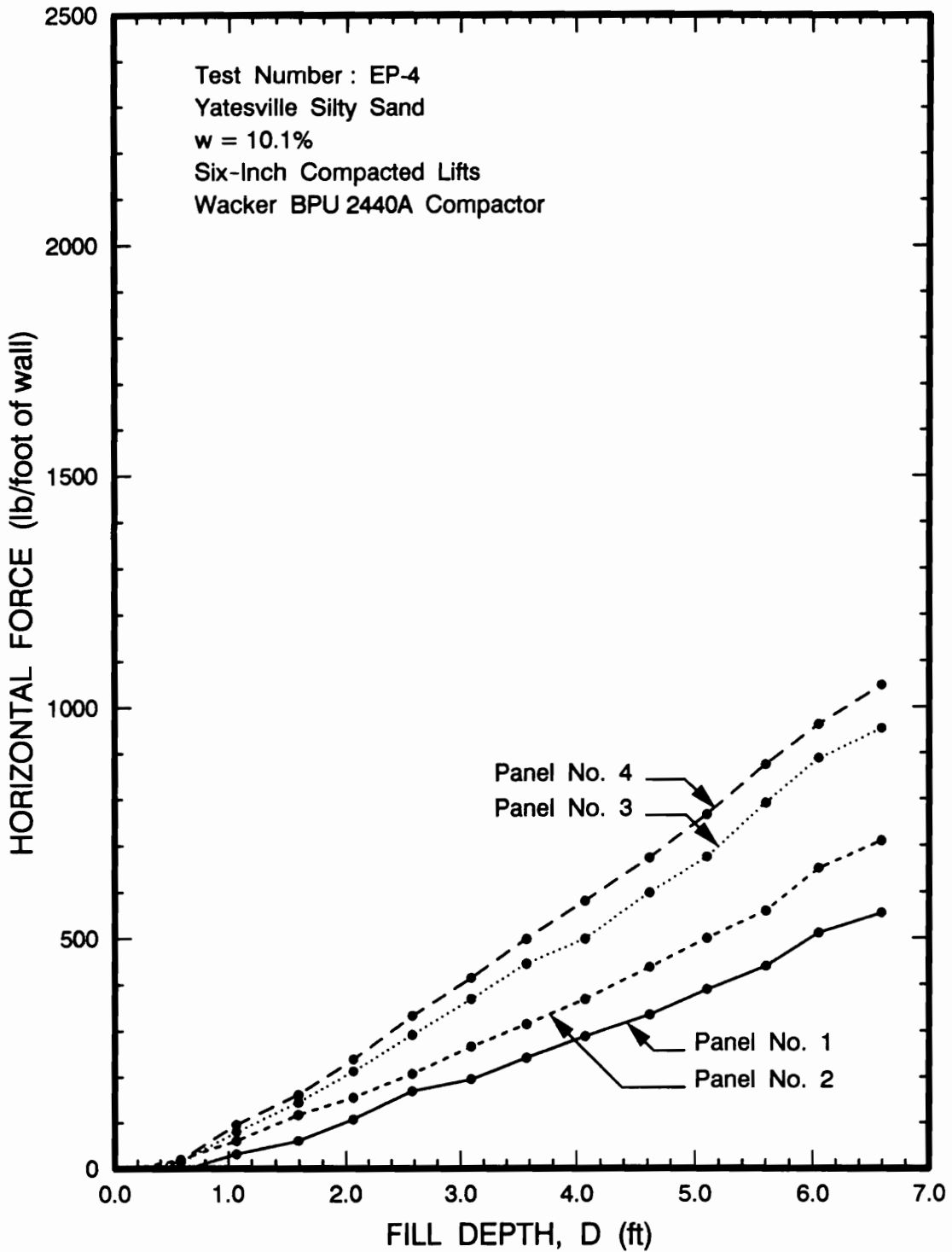


Figure 6.13) Measured Horizontal Force for each Wall Panel as a Function of Fill Depth for Test EP-4.

- 5) Comparing the horizontal forces of tests EP-1 and EP-2 with those of test EP-3 indicates that increasing the compacted lift thickness from four inches to six inches causes a significant reduction in the lateral force exerted on the wall panels.
- 6) Comparing the horizontal forces of test EP-3 with those of test EP-4 indicates that, for the Yatesville silty sand, reducing the water content from 13.7 percent to 10.1 percent reduced the measured horizontal forces by about 25 percent. As indicated in Table 6.2, the average dry density for test EP-4 was 106 lb/ft³. This value is about 12 percent less than that of the other three tests.

The unexpected wide range and the consistent trend of the horizontal forces experienced by the four panels may be caused in part by the physical configuration of the Instrumented Retaining Wall Facility and in part by the test procedures. Panel 1, which consistently experienced the smallest horizontal force, is located next to the endwall of the facility. This situation creates two problems: 1.) the interaction between the concrete endwall and the compacted backfill may reduce the horizontal force exerted on Panel 1, and 2.) the presence of the endwall and the configuration of the compactor make it difficult to properly compact the backfill near the endwall resulting in a reduced unit weight and lateral pressure for the backfill in this area.

The use of a Bobcat 643 loader to bring the backfill into the retaining wall facility may have produced higher than normal lateral pressures against Panels 3 and 4. During the placement of a new layer of fill, the loader was driven on the surface of the compacted fill in

the ramp area and next to Panels 3 and 4. The loader was only operated next to Panels 3 and 4 with more of the activity next to Panel 4. There may also have been a small effect on the pressures at Panel 2, as a result of the loader activity and stress distribution within the backfill.

The range of the measured forces and the differences between forces experienced by the four panels are believed to be primarily due to the factors discussed above and they can probably be reduced or eliminated in future tests through the use of improved testing procedures.

6.4.3 Measured Vertical Forces

The vertical shear force exerted on the wall, as a result of soil-wall interaction, is measured by two vertical load transducers at the base of each panel. The vertical shear forces acting on the four wall panels are shown in Figures 10.14 through 10.17 for tests EP-1 through EP-4. The figures present the vertical force, in pounds per linear foot of wall, as a function of fill depth.

Based on Figures 10.14 through 10.17, the following observations are made:

- 1) For test EP-1, the vertical shear force of all four panels increased during the 12.5 hour intermission.
- 2) There is an appreciable variation in the vertical shear force acting on the different wall panels during a given test. The variation is greater for test EP-1 and EP-2, having a compacted lift thickness of

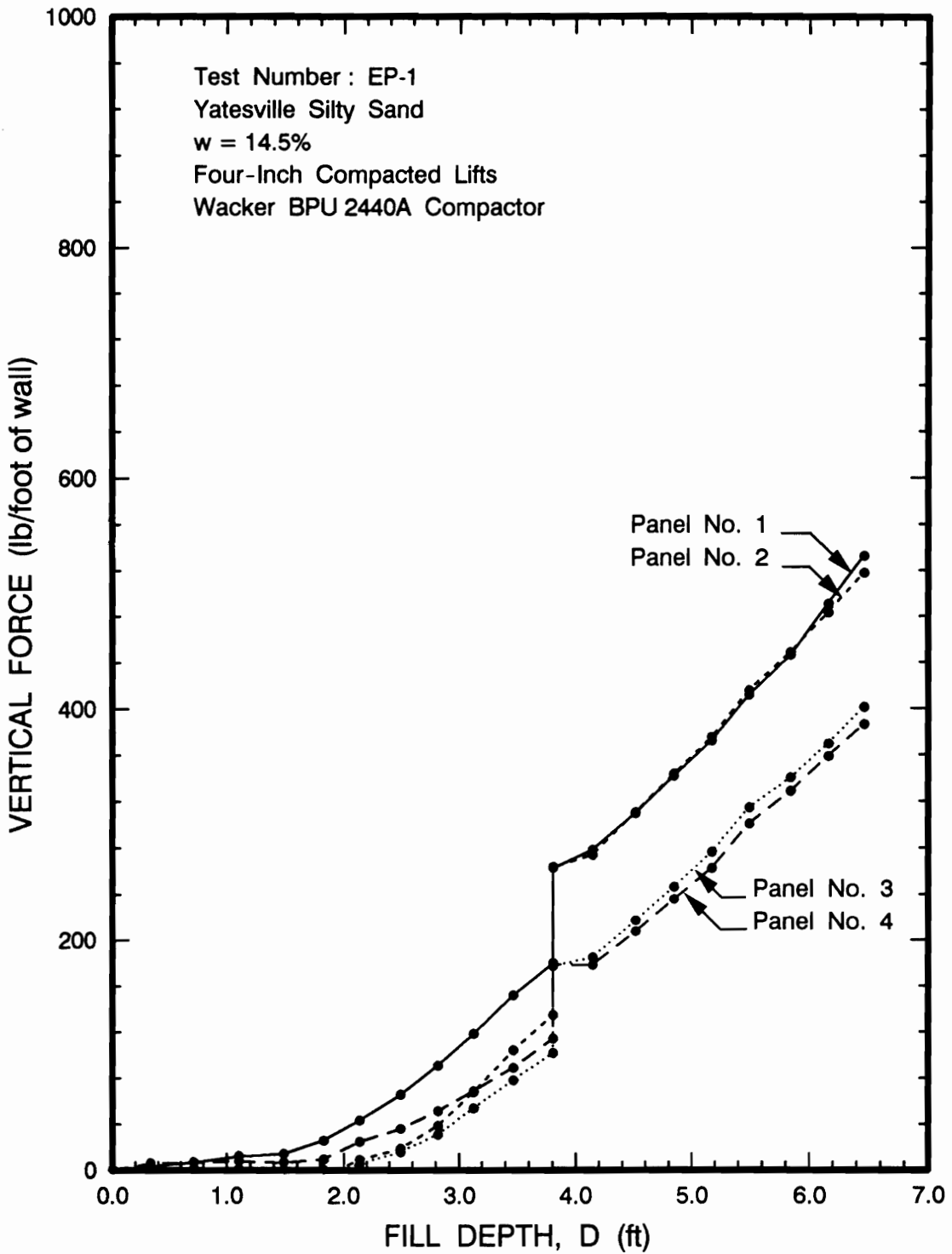


Figure 6.14) Measured Vertical Force for each Wall Panel as a Function of Fill Depth for Test EP-1.

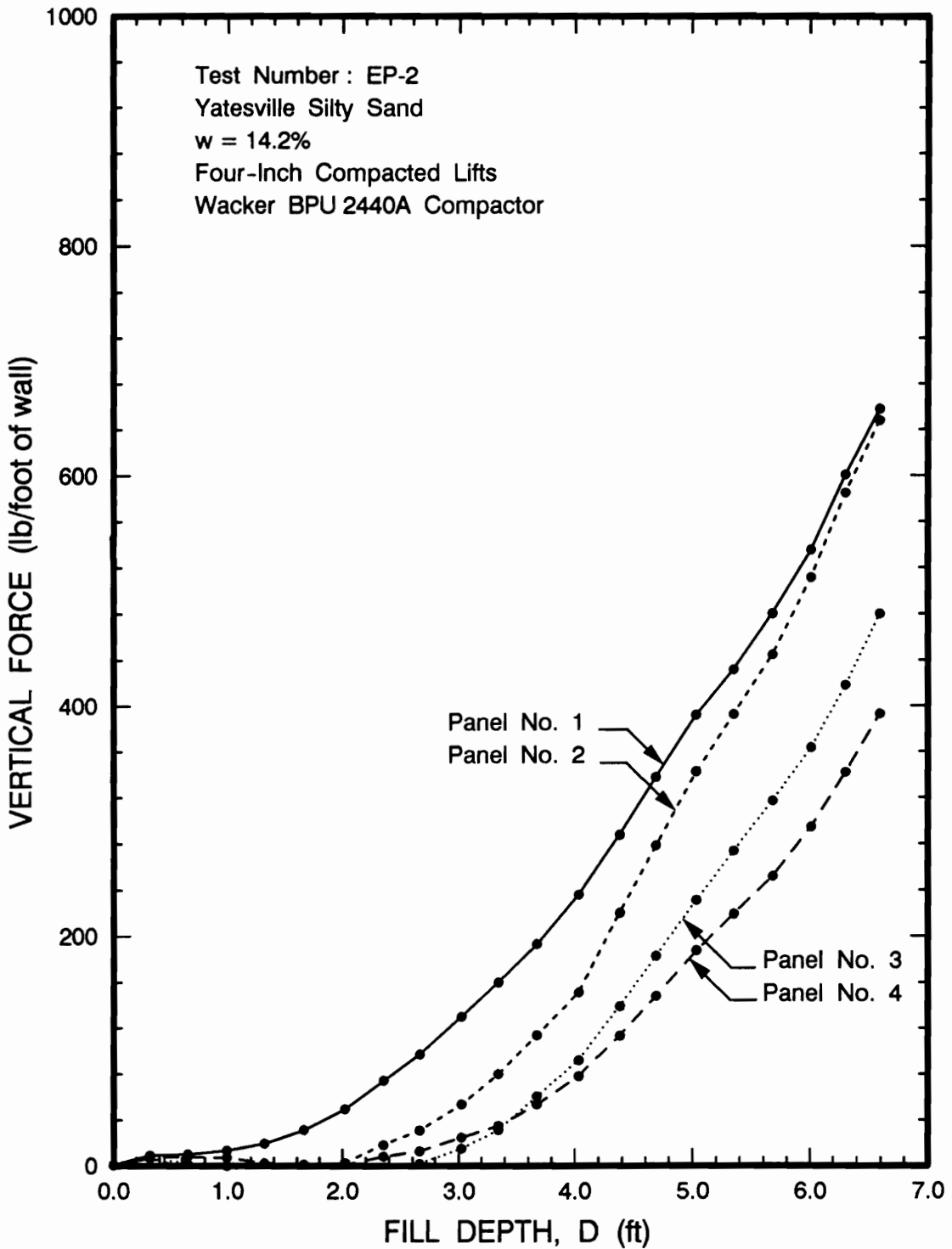


Figure 6.15) Measured Vertical Force for each Wall Panel as a Function of Fill Depth for Test EP-2.

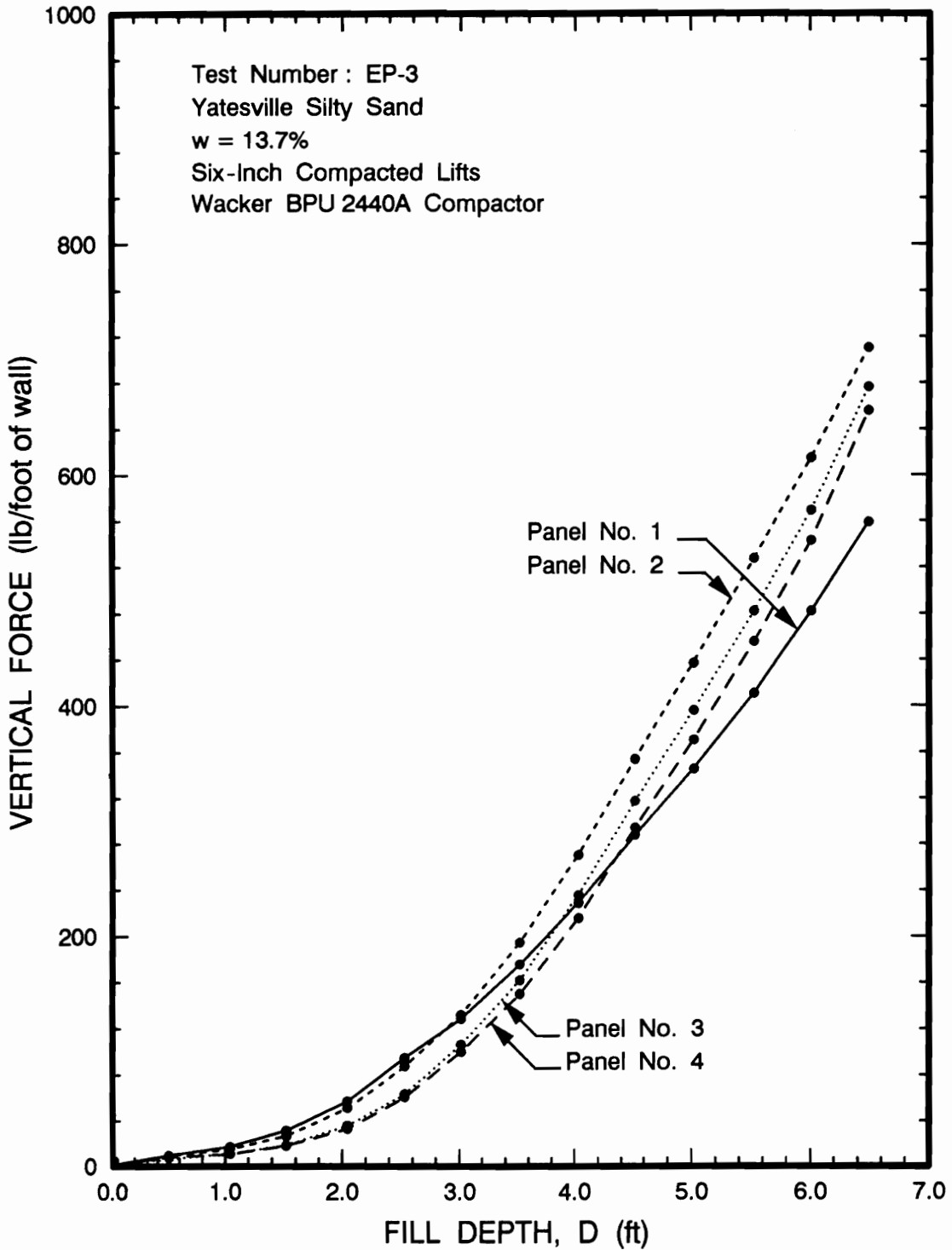


Figure 6.16) Measured Vertical Force for each Wall Panel as a Function of Fill Depth for Test EP-3.

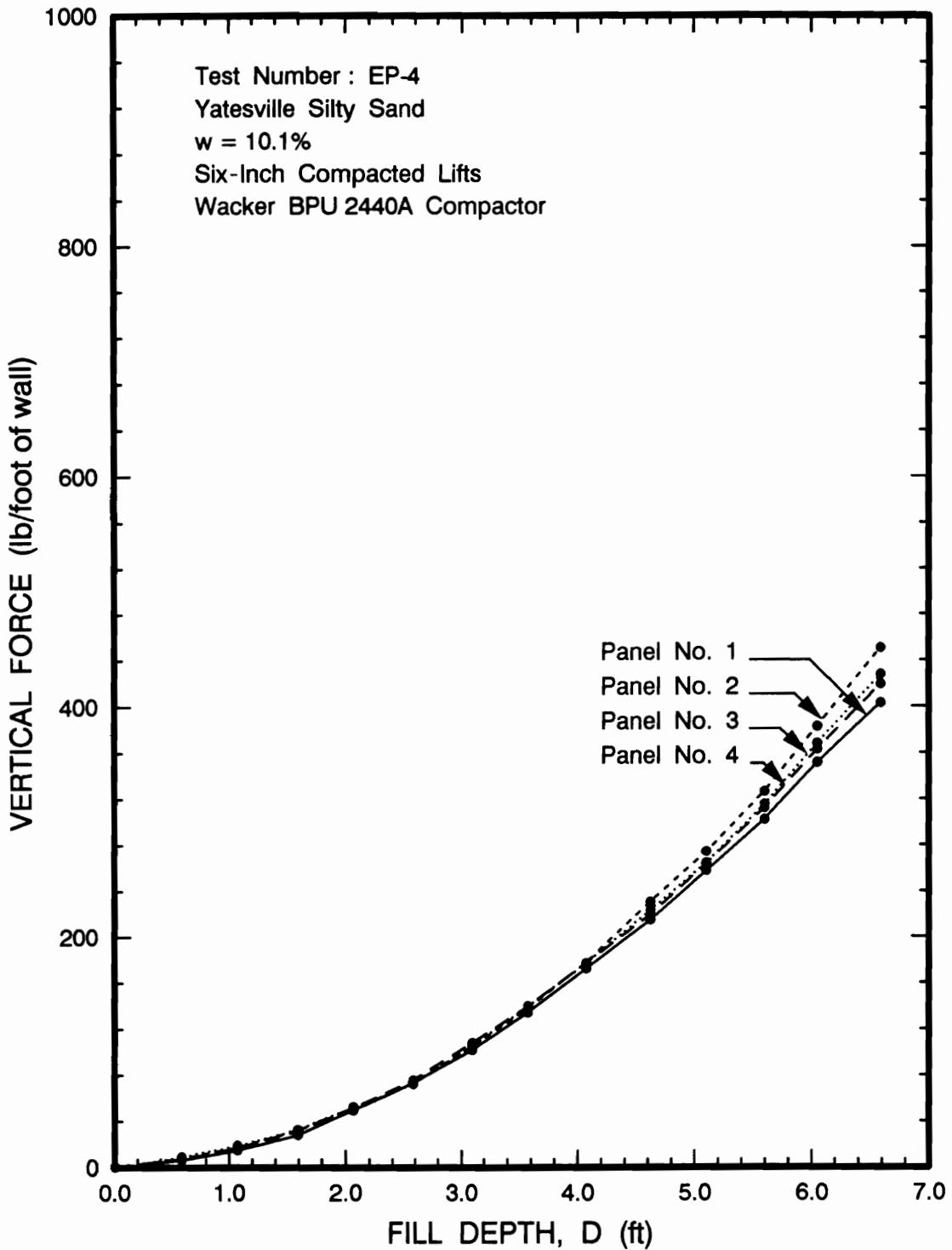


Figure 6.17) Measured Vertical Force for each Wall Panel as a Function of Fill Depth for Test EP-4.

four inches, than for tests EP-3 and EP-4, with a compacted lift thickness of six inches.

- 3) With the exception of Panel 1, there is a consistent relationship between the vertical forces experienced by the panels. During the later phases of backfilling, the vertical shear force on Panel 3 is usually less than that on Panel 2 and greater than that on Panel 4.
- 4) The magnitude of the shear forces and the variation among the four panels were smallest for test EP-4 where the compacted lift thickness was six inches and the moisture content and dry unit weight of the backfill were significantly lower than for the other three tests.

6.4.4 Magnitude and Location of the Horizontal Force Resultant

The magnitude and location of the horizontal force resultant can be interpreted from two different groups of measurements. First, the horizontal-force transducer measurements can be used to determine the magnitude of the resultant. Its location can be determined using moment equilibrium and including the effect of the couple produced by the vertical shear force on the face of the wall panels and the vertical support reactions, which are centered beneath the panels. Second, the earth pressure cell measurements can be used to represent the pressure distribution on the face of the wall panels from which the magnitude and location of the horizontal force resultant can be determined.

To determine the magnitude of the horizontal force resultant and its point of application based on the earth pressure cell data, the measured pressures were used to create an incremental pressure-depth profile as

shown in Figure 6.18. For a given construction step, each earth pressure cell was assigned a tributary height, and the pressure was taken to be constant over that height. The shallowest pressure cell was assigned a tributary height equal to its depth below the surface plus one-half the distance to the next deeper pressure cell. The bottom pressure cell was assigned a tributary height of thirteen inches and each intermediate pressure cell was assigned a tributary height equal to the six vertical spacing interval of the pressure cells. At elevations with more than one pressure cell, an average pressure value was used. Pressure cells less than three inches below the surface of the backfill were not used. The area of the incremental pressure diagram represents the magnitude of the horizontal force resultant and the vertical position of the centroid of the pressure diagram represents the height of the point of application of the force resultant.

This method of calculating the magnitude and point of application of the horizontal force resultant, although very simple, provides a reasonable representation of the pressure distribution and is easily incorporated into data reduction procedures. Since the method is systematic, each case is treated the same and biases in the interpretation of the test results are reduced.

The two approaches described above were used to calculate the magnitude and location of the horizontal force resultant as a function of fill depth for tests EP-2 through EP-4. The resulting information is presented in Figures 6.19 through 6.21.

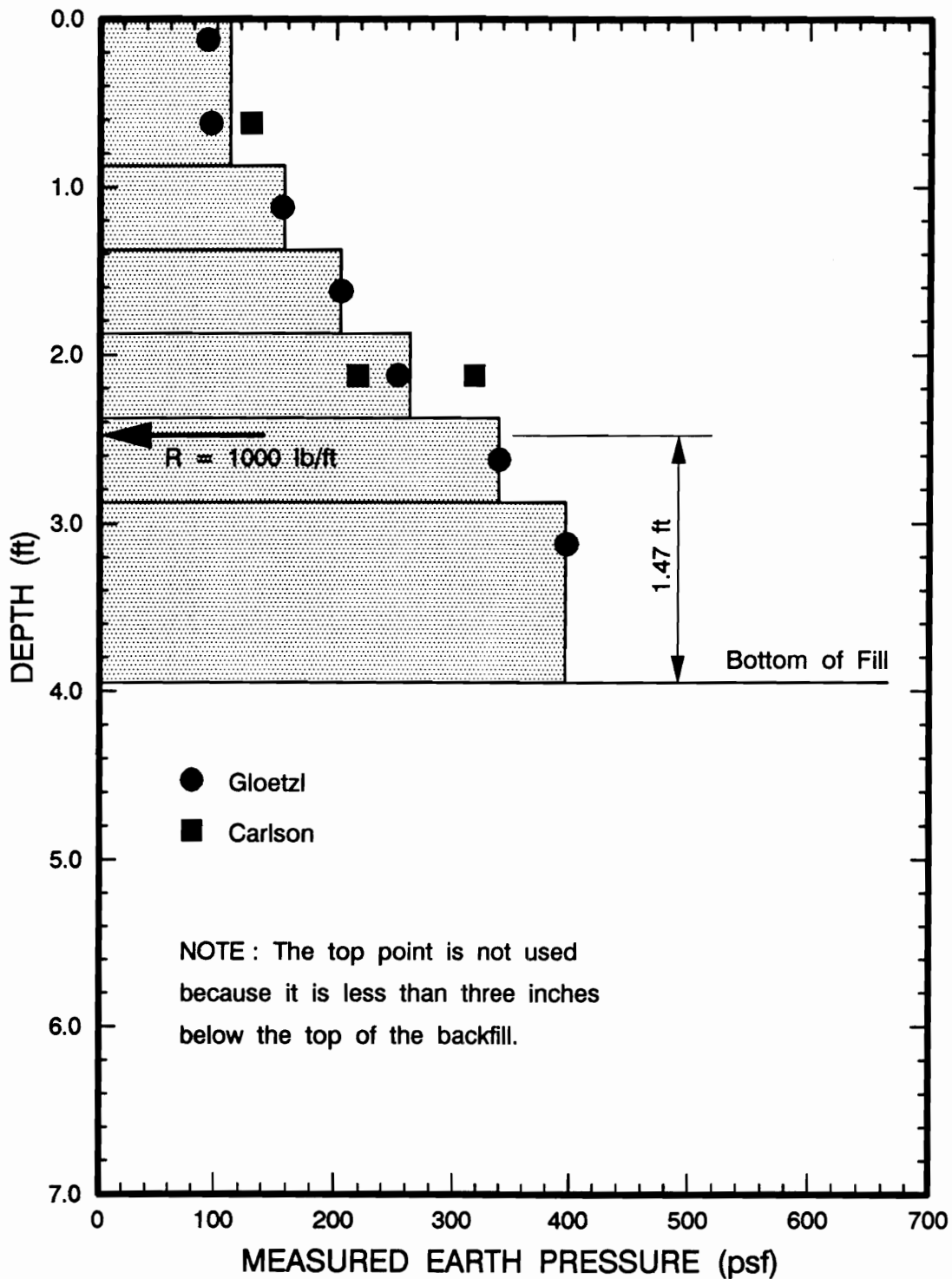


Figure 6.18) Incremental Pressure-Depth Profile used to Represent the Measured Pressures for Calculation of the Magnitude and Point of Application of the Horizontal Force Resultant.

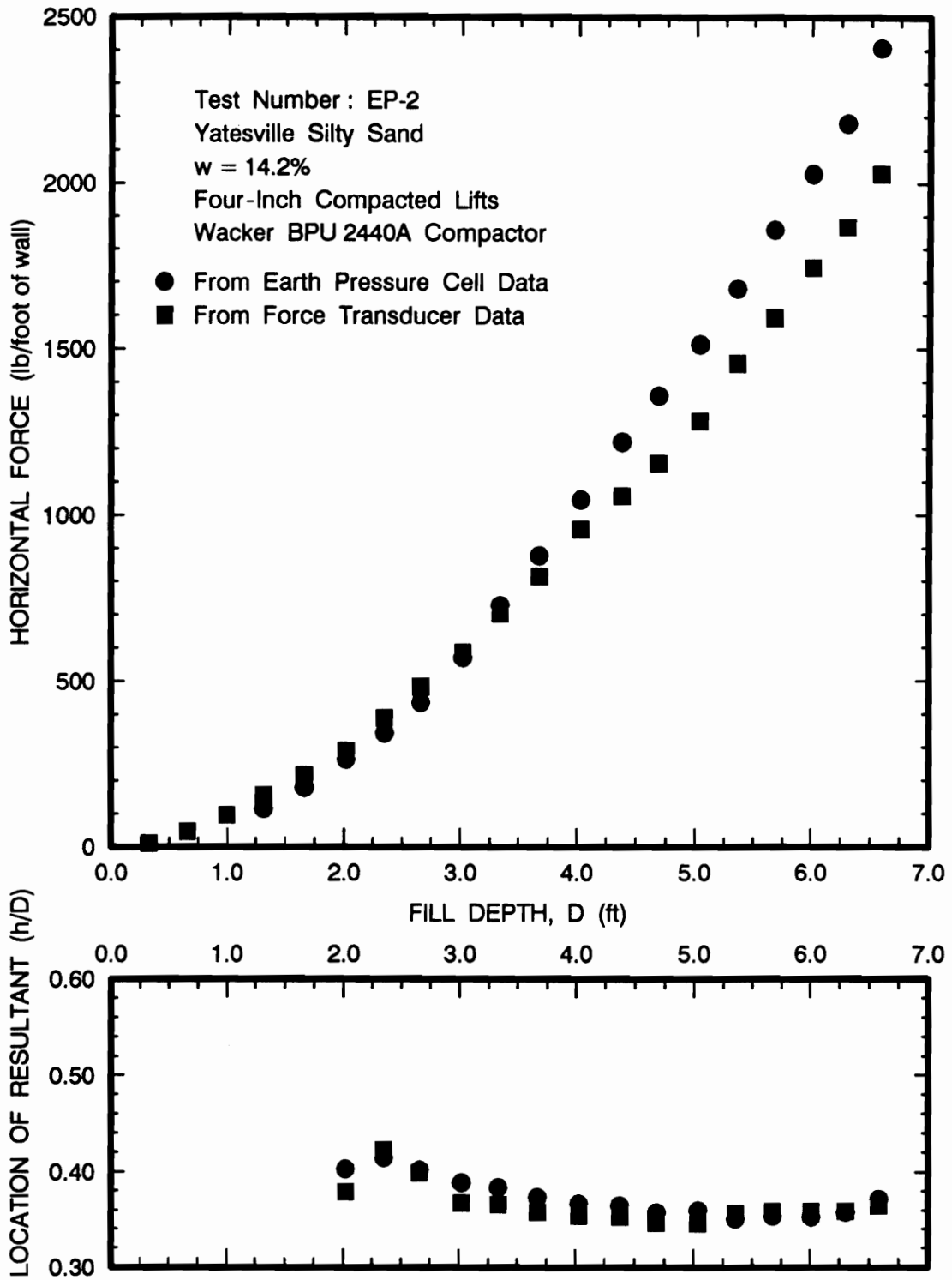


Figure 6.19) Magnitude and Location of the Horizontal Force Resultant as Functions of Fill Depth for Test EP-2.

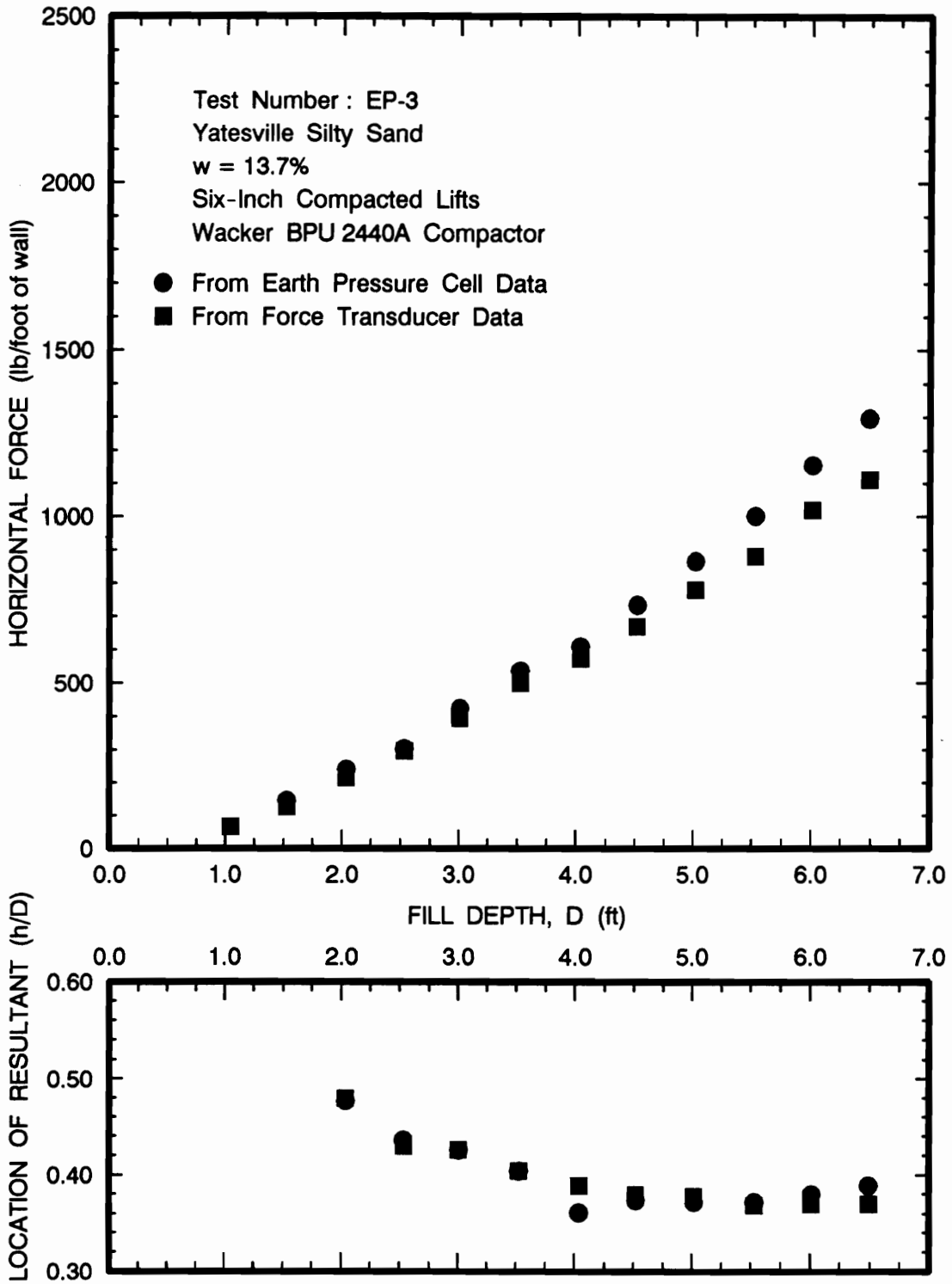


Figure 6.20) Magnitude and Location of the Horizontal Force Resultant as Functions of Fill Depth for Test EP-3.

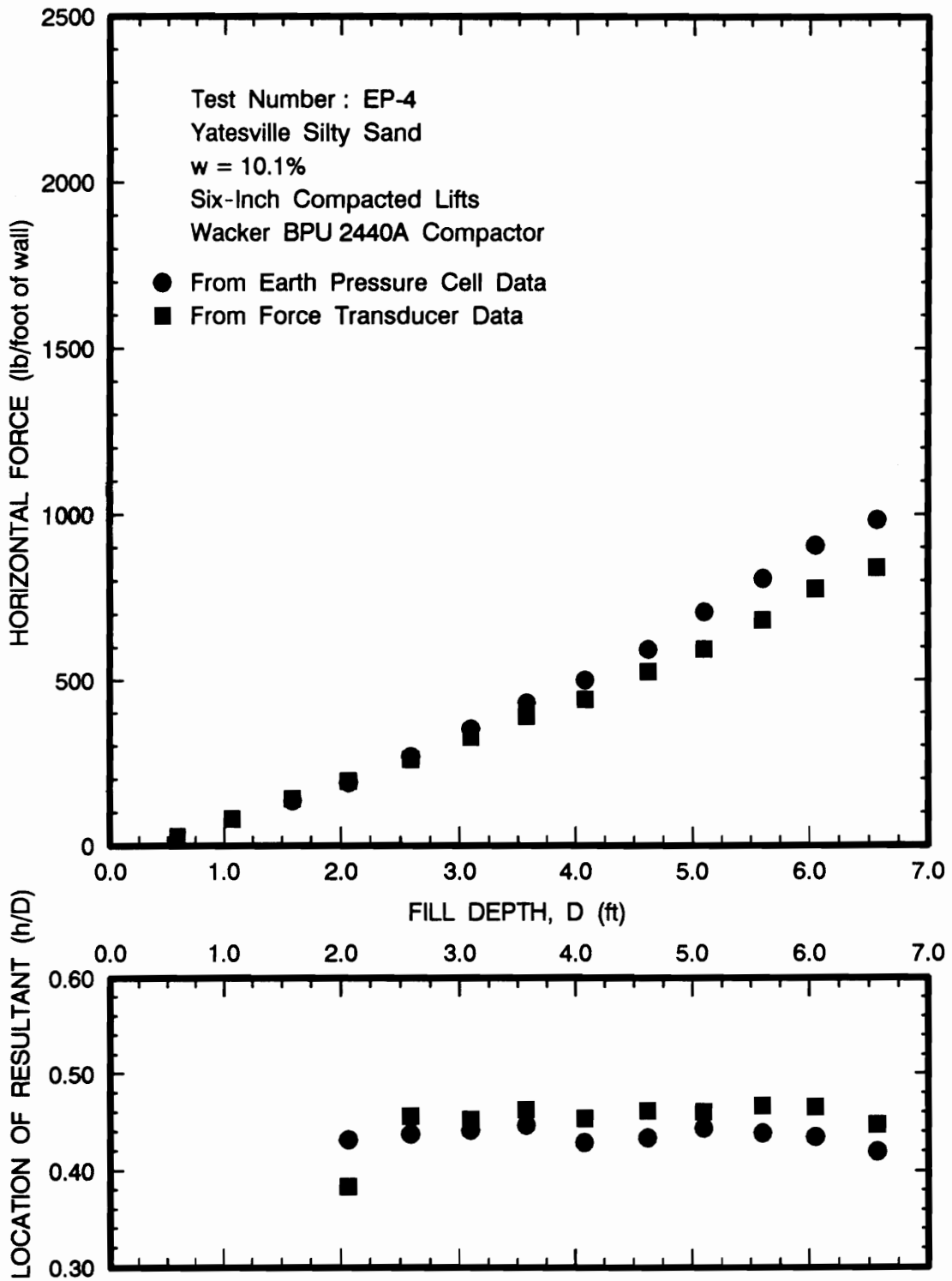


Figure 6.21) Magnitude and Location of the Horizontal Force Resultant as Functions of Fill Depth for Test EP-4.

The figures are based on measurements obtained from panels 2 and 3 because only these two panels were instrumented with earth pressure cells and, as discussed earlier, the forces recorded at Panels 1 and 4 are probably those most likely to be in error due to the configuration of the facility and the test procedures. Test EP-1 has been eliminated from further consideration because, according to Table 6.2, it is very similar to test EP-2 and it involves the added complication of an overnight intermission, making direct comparisons with the other three tests difficult.

Based on Figures 6-19 through 6.21, the following observations are made:

- 1) For fill depths greater than about 3.5 feet, the horizontal forces calculated from force transducer data are consistently smaller than those calculated from the earth pressure cell data. However, the difference is less than about 20 percent of the average value.
- 2) For fill depth less than about 3.5 feet, there is very good agreement between the values calculated from the two groups of measurements.
- 3) The horizontal force is considerably larger for test EP-2, with a compacted lift thickness of four inches, than for test EP-3, with a compacted lift thickness of six inches.
- 4) For the Yatesville silty sand and a compacted lift thickness of 6 inches, reducing the water content from 13.7 percent to 10.1 percent results in a reduction of the horizontal force of about fifteen percent with very little change in the relationship between the values calculated from the two different types of data. This change

in water content also produced a change in the location of resultant from about 0.38 to about 0.43, times the depth of the backfill.

5) For tests EP-2 and EP-3, the location of the horizontal force resultant at the end of construction is between 0.36 and 0.39 times the fill depth. This indicates that, for this backfill material, changing the compacted layer thickness from four inches to six inches has little effect on the position of the resultant force.

The general agreement between the values for the magnitude and location of the resultant horizontal force calculated from the two independent measurement systems provides an added degree of confidence in the observed values. This is particularly important to support the accuracy of the earth pressure measurements which often involve inaccuracies due to a number of factors. The distribution of the earth pressures on the wall will be discussed in a later section.

The values for the location of the horizontal force resultant are between one-third and one-half of the fill depth, as is generally expected for compacted backfills.

6.4.4.1 Time Dependence of the Magnitude and Location of the Horizontal Force Resultant

The same procedures used to calculate the location and magnitude of the horizontal force resultant from both the force transducer data and the earth pressure cell data for the period during backfilling was used to evaluate these values at a number of times after the end of

construction. The resulting information is presented in Figures 6.22 through 6.24 as a function of time since the end of backfilling.

The magnitudes of the horizontal forces calculated from the two groups of data agree fairly well for the first few hours after construction but then, for tests EP-2 and EP-3, the values from the two methods tend to diverge. For test EP-4, the agreement between the values obtained from the two groups of data tends to increase during the first day after construction and remains good for the rest of the five-day observation period.

The variation in the location of the resultant as a function of time is similar to that of the magnitude of the resultant. For test EP-4, the location of the resultant changes very little over the five-day period. In contrast to this, the locations of the resultant calculated from the two sets of data for both tests EP-2 and EP-3 are different by about 0.06 times the height of the fill for times more than one day after construction.

6.4.5 Vertical Shear Force and Mobilized Wall Friction

The horizontal and vertical reaction forces of the wall panels were monitored with the force transducers that support each panel. For Panels 2 and 3, this information was used to investigate the magnitude of the vertical shear force and the corresponding wall friction angle as functions of the backfill depth. This information is shown in Figures 6.25 through 6.27 for tests EP-2 through EP-4.

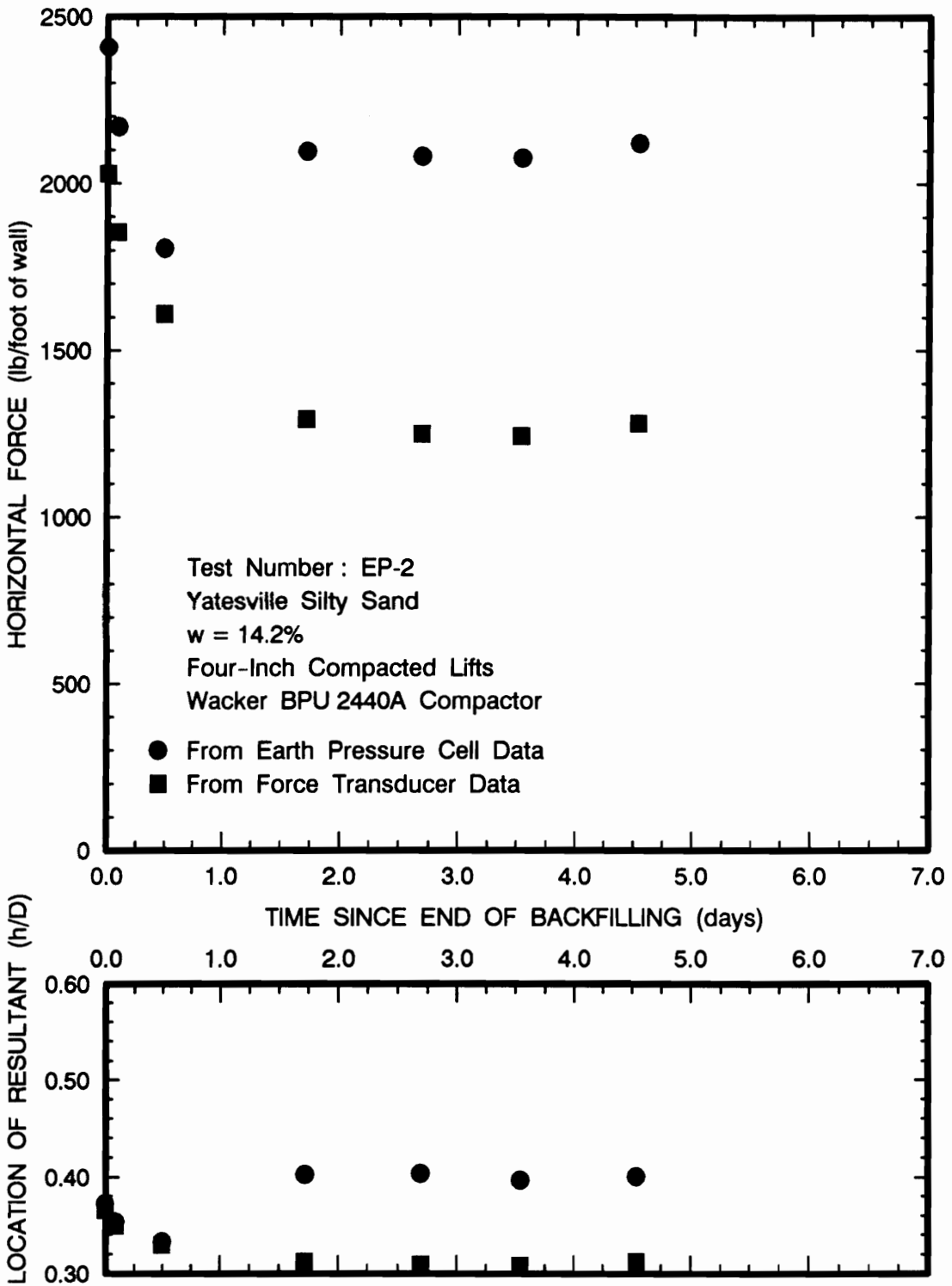


Figure 6.22) Magnitude and Location of the Horizontal Force Resultant as Functions of Time for Test EP-2.

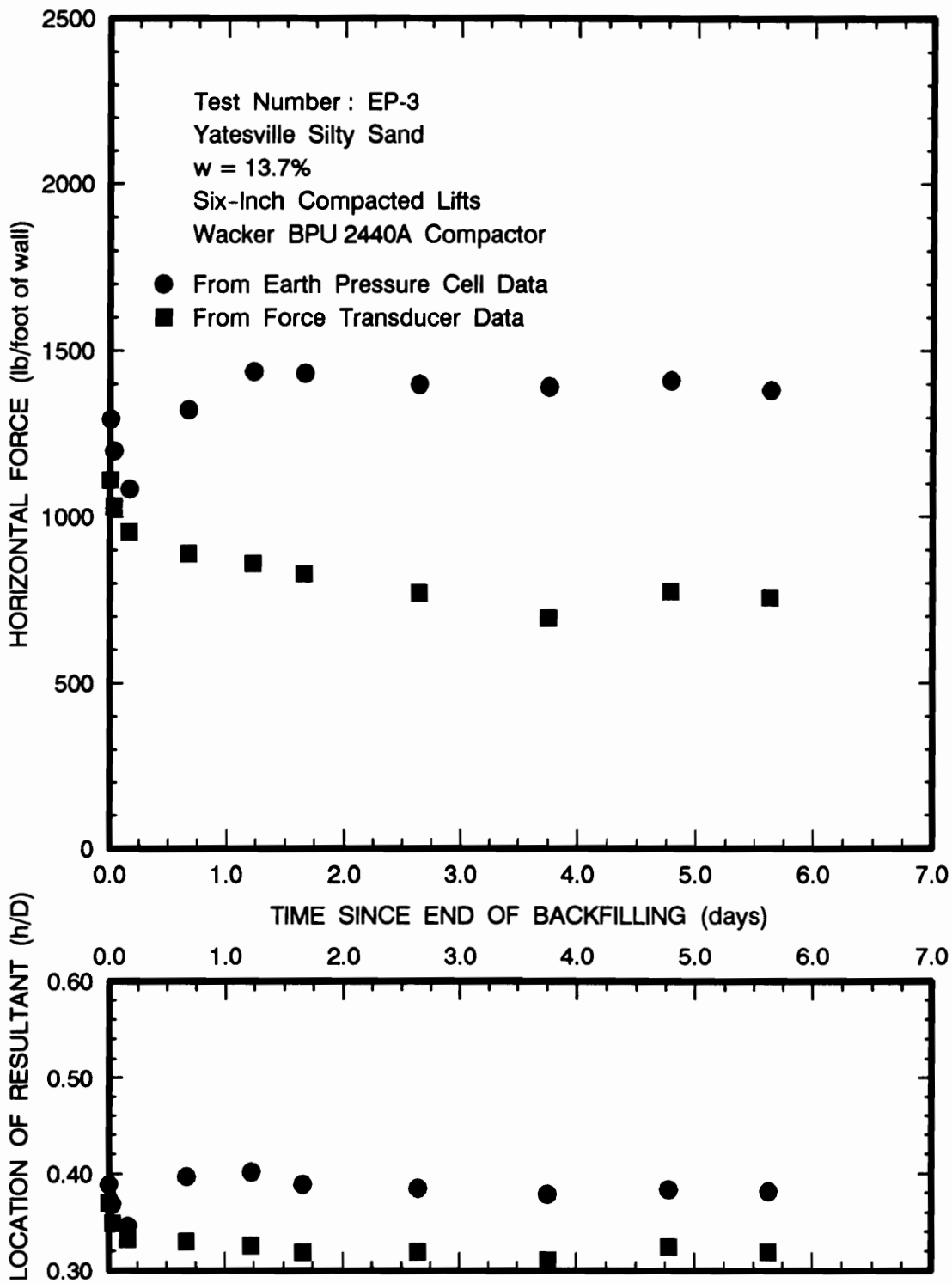


Figure 6.23) Magnitude and Location of the Horizontal Force Resultant as Functions of Time for Test EP-3.

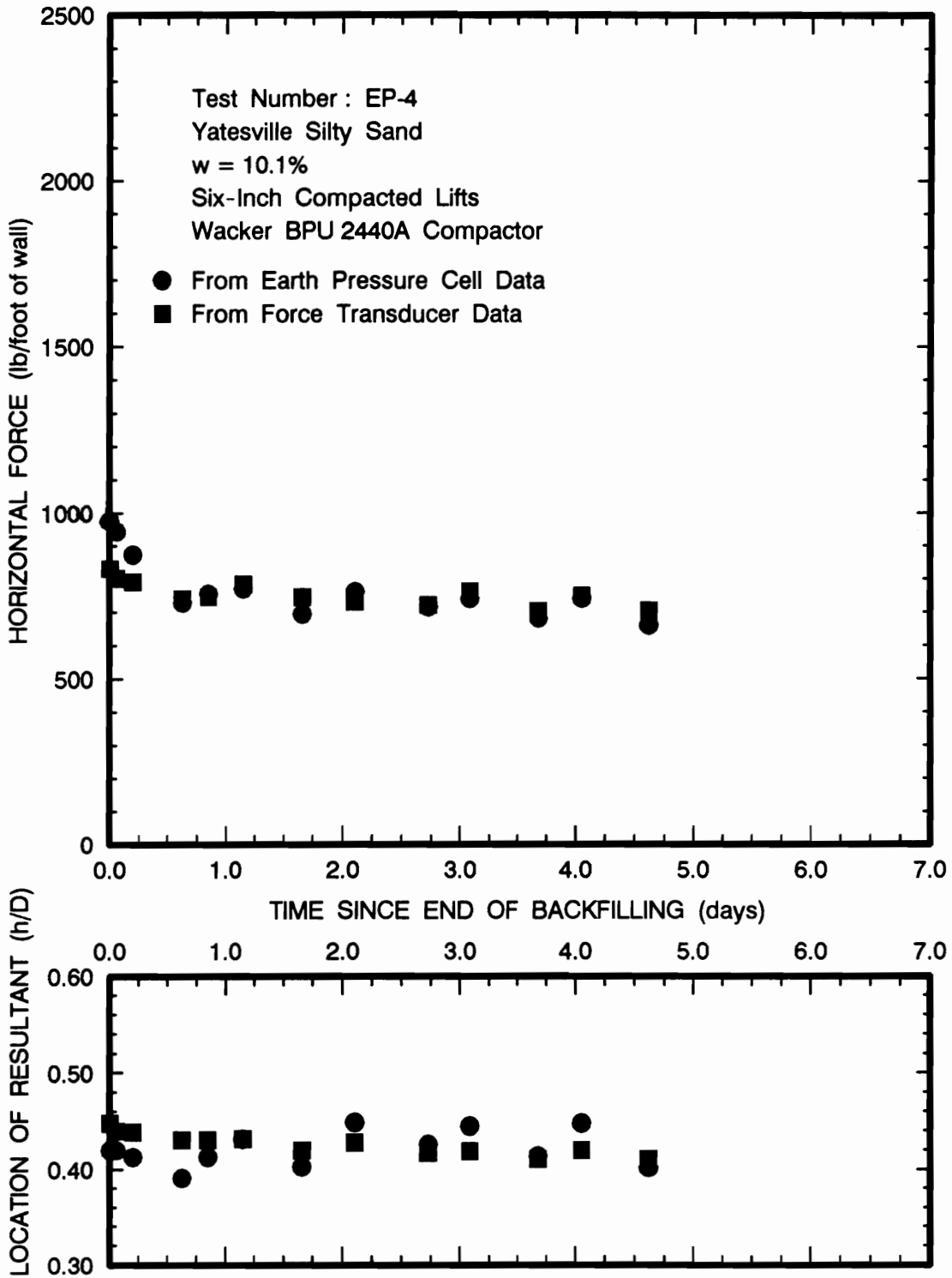


Figure 6.24) Magnitude and Location of the Horizontal Force Resultant as Functions of Time for Test EP-4.

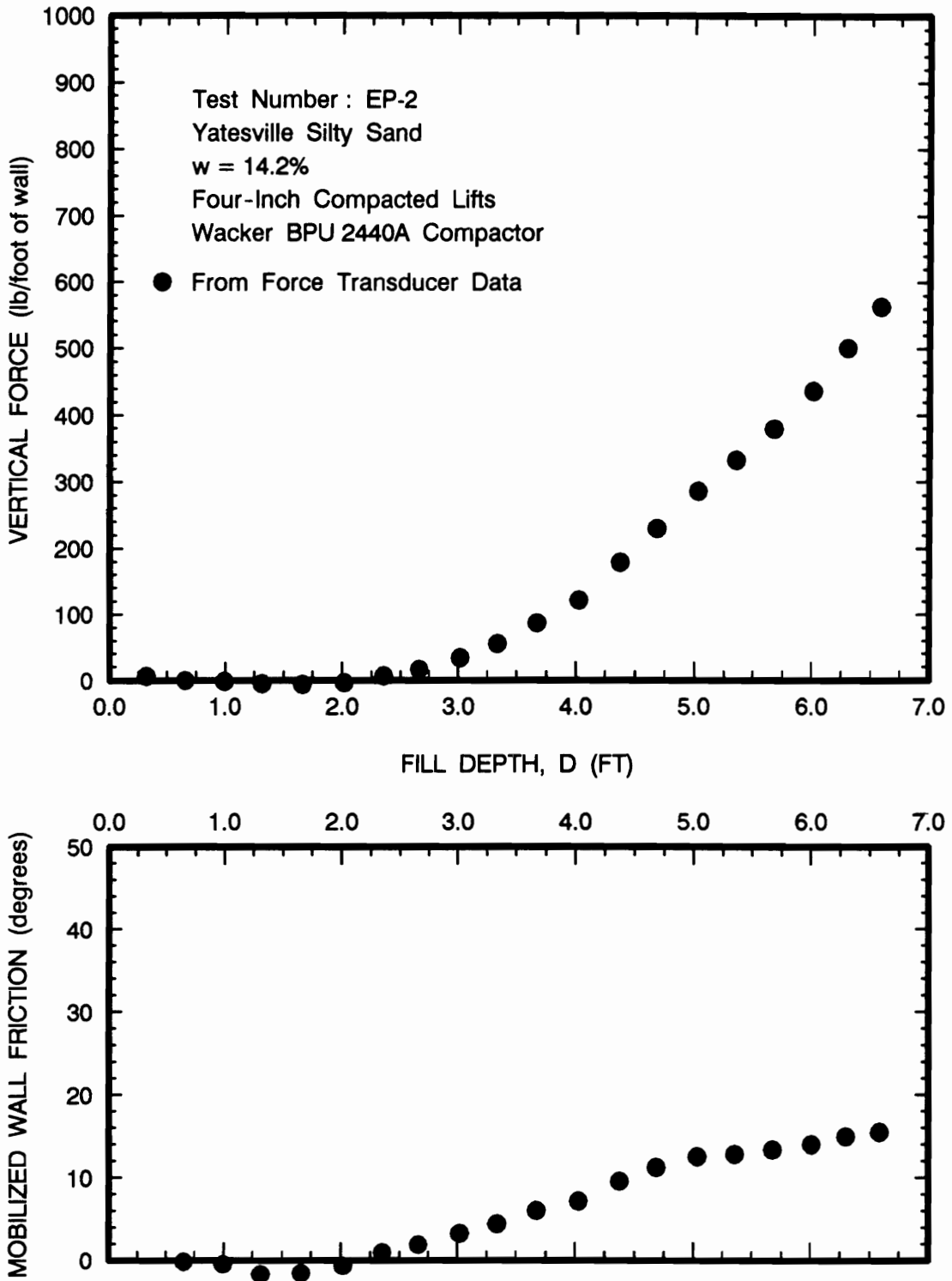


Figure 6.25) Vertical Shear Force and Mobilized Wall Friction as Functions of Fill Depth for Test EP-2.

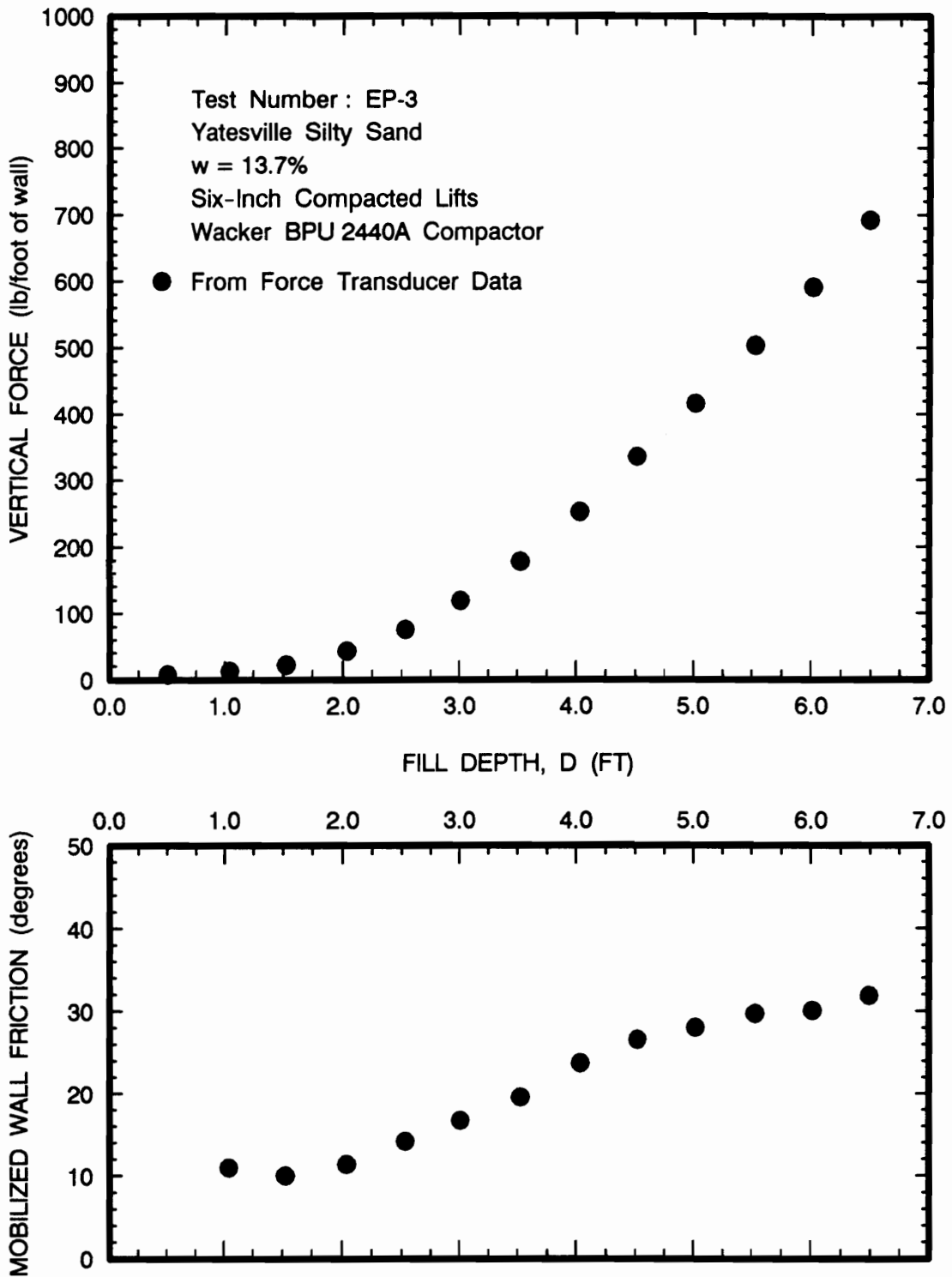


Figure 6.26) Vertical Shear Force and Mobilized Wall Friction as Functions of Fill Depth for Test EP-3.

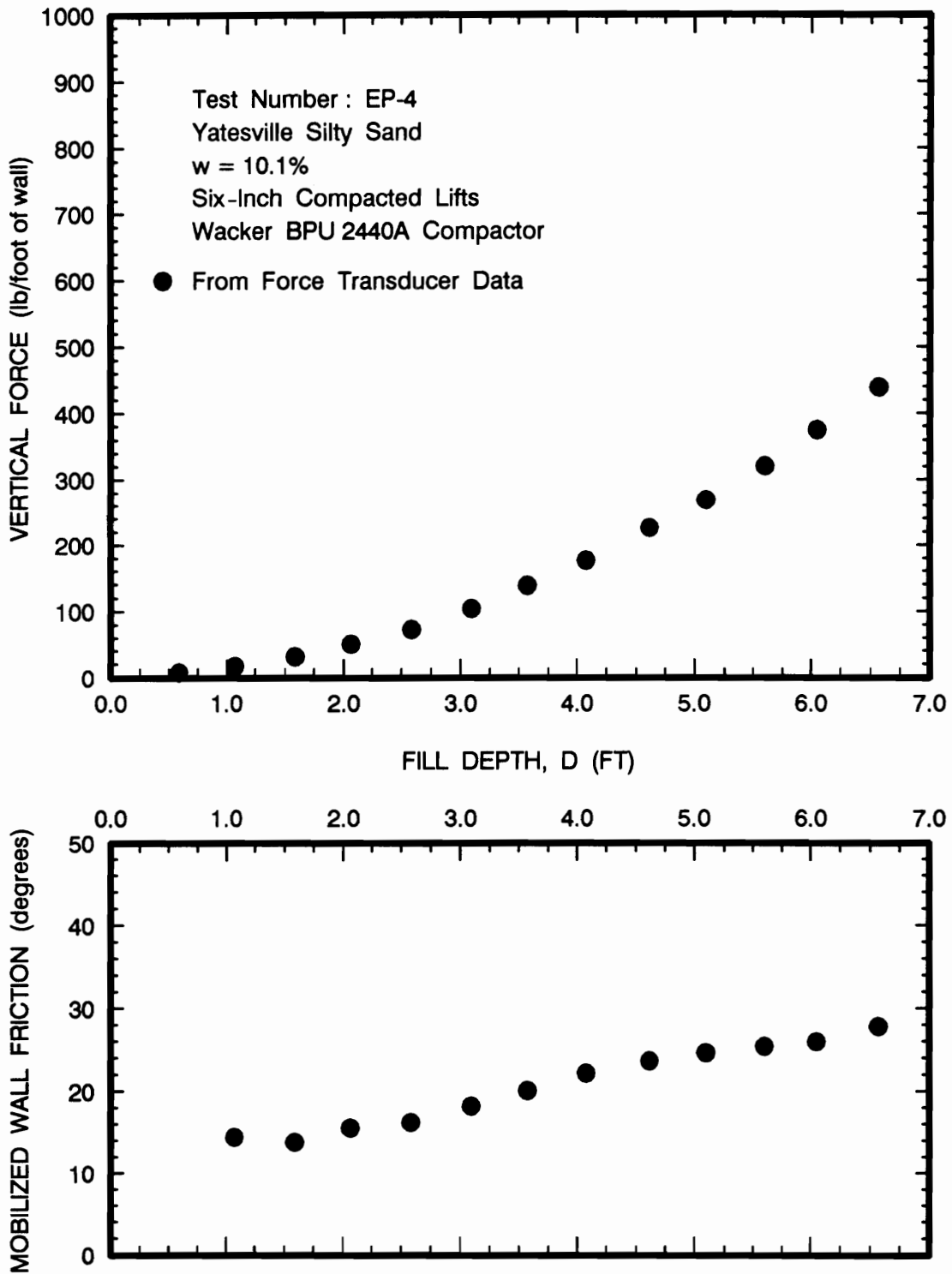


Figure 6.27) Vertical Shear Force and Mobilized Wall Friction as Functions of Fill Depth for Test EP-4.

The vertical shear force per linear foot of wall shown in these figures is the total vertical force experienced by these panels divided by their five-foot combined width. The mobilized wall friction is presented in degrees and represents the angle whose tangent is equal to the ratio of the total horizontal force to the total vertical force of the panels.

For Yatesville silty sand, comparing Figures 6.19 and 6.25 from test EP-2 with Figures 6.20 and 6.26 from test EP-3 indicates that: while the measured horizontal force is significantly less for six-inch compacted lifts than for four-inch compacted lifts, the reverse is true of the measured vertical force. This fact is emphasized by the lower portions of Figures 6.25 and 6.26 which indicate that the mobilized wall friction angle during test EP-3 is about 6 to 8 degrees more than that during test EP-2.

The effect of compaction water content on the vertical force experienced by the wall and the mobilized wall friction angle is seen by contrasting Figure 6.26 from test EP-3 with Figure 6.27 from test EP-4. These figures indicate that reducing the water content from 13.7 percent to 10.1 percent produced a definite reduction in the vertical shear force acting on the wall but there was little effect on the mobilized wall friction angle. The change in the mobilized wall friction angle is small because the change in water content caused changes in the horizontal and vertical forces that are of similar proportions. The compacted lift thickness and number of passes of the compactor were the same for these two tests.

6.4.5.1 Time Dependence of the Vertical Shear Force and the Mobilized Wall Friction

The vertical shear force and the mobilized wall friction are shown in Figures 6.28 through 6.30 as a function of time for tests EP-2 through EP-4. These values were calculated from the horizontal and vertical force transducer data of Panels 2 and 3 as discussed in the previous section.

The vertical shear force experienced by Panels 2 and 3 increases noticeably during the first few hours after construction for all three tests. For tests EP-2 and EP-4 the increasing of the vertical forces continues into the second day, after which the values remain nearly constant for the remainder of the 4.5 day observation period. Four and one-half days after construction, the shear force for test EP-4 was 23 percent larger than the end of construction shear force. For test EP-2, the increase represented about 42 percent of the end of construction value. For test EP-3, the final value of the vertical shear force was only slightly above the end of construction value.

The change in the mobilized wall friction for tests EP-2 and EP-4, as a function of time after construction, reflects the change in the vertical shear force of these tests. The value of the mobilized wall friction increases shortly after construction and then is relatively constant during the remainder of the test.

For test EP-3, the mobilized wall friction increases initially and tends toward a constant value that is about eleven degrees greater than the end of construction value. For this test, the increase in the value

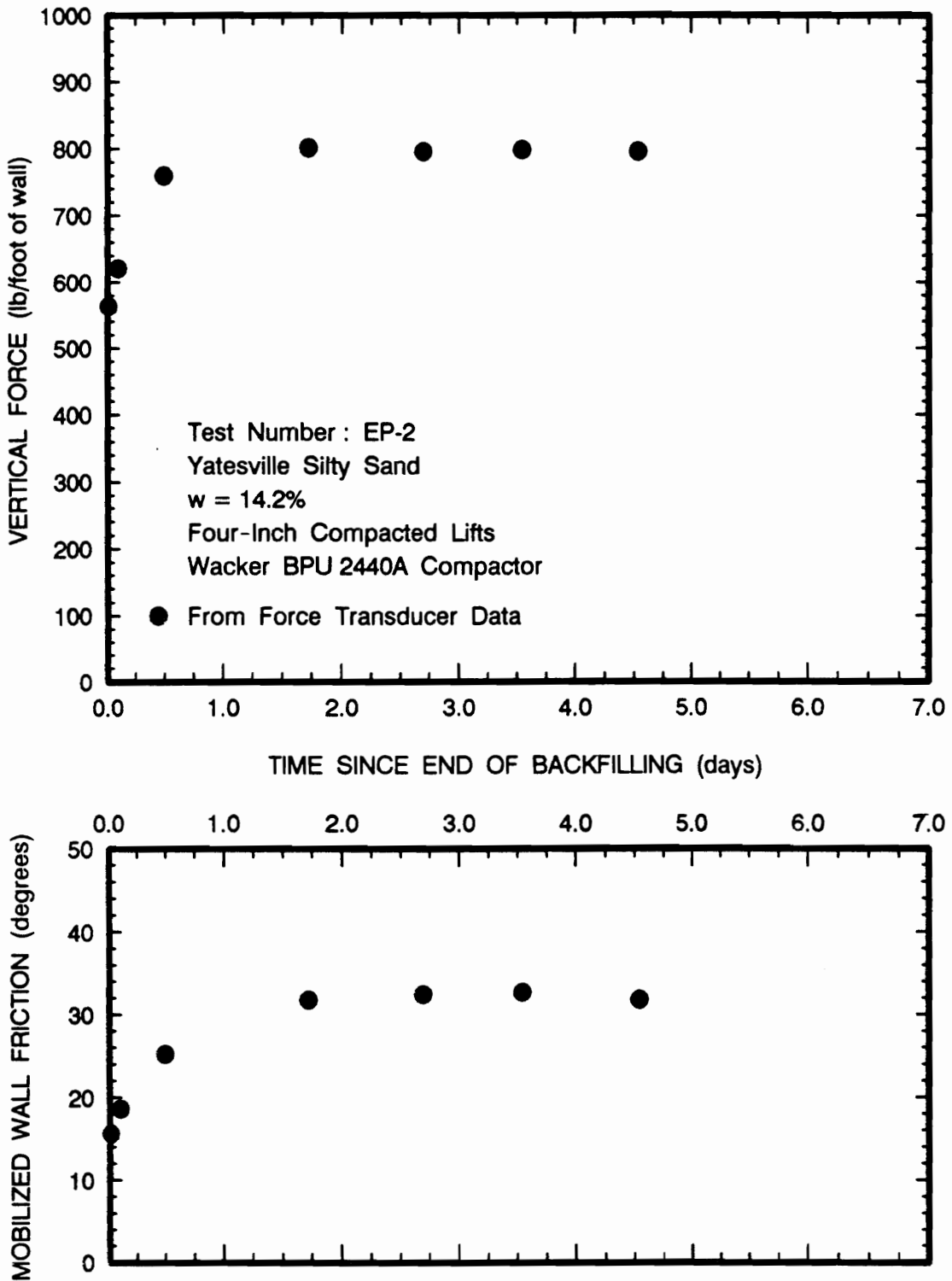


Figure 6.28) Vertical Shear Force and Mobilized Wall Friction as Functions of Time for Test EP-2.

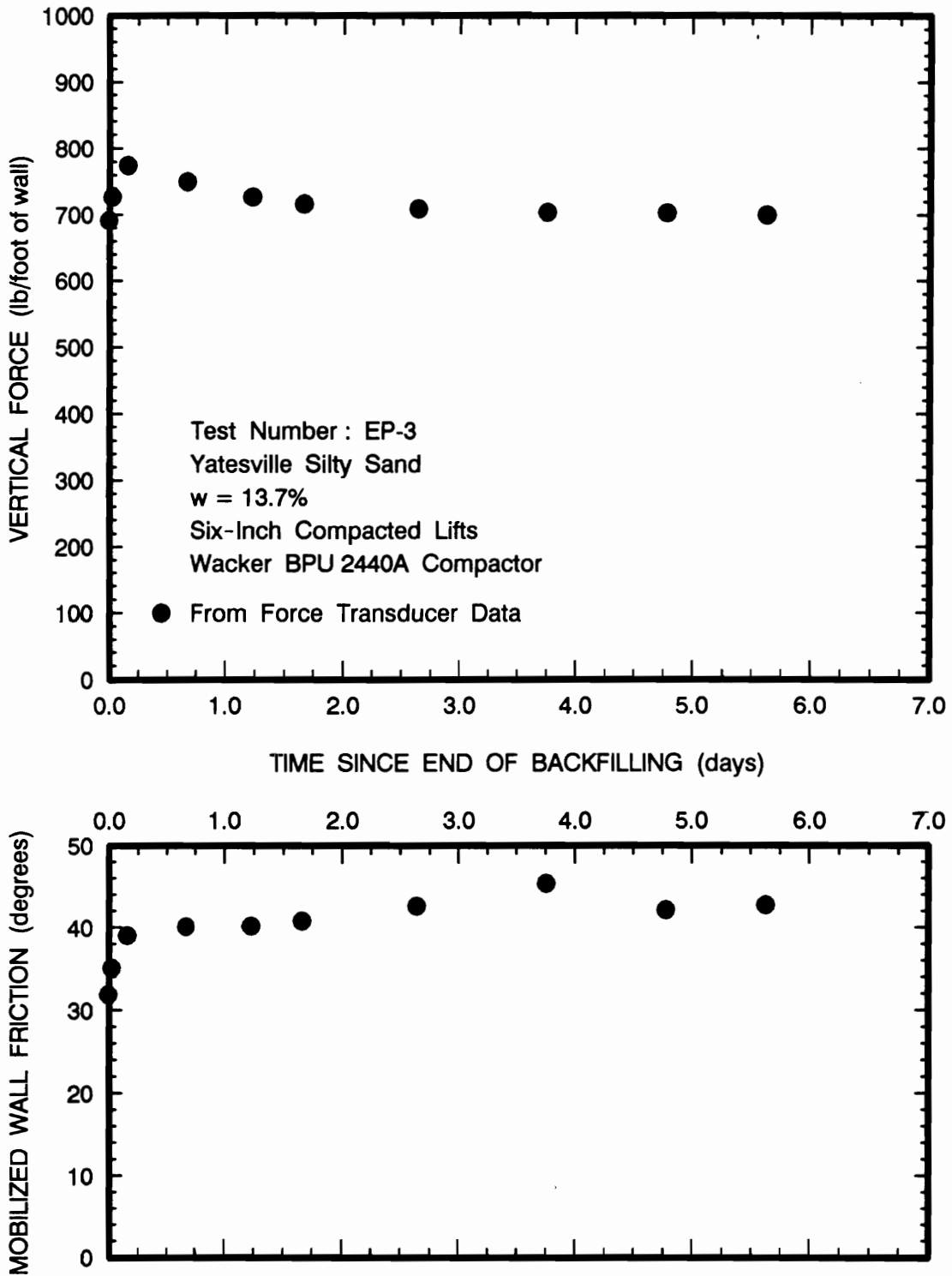


Figure 6.29) Vertical Shear Force and Mobilized Wall Friction as Functions of Time for Test EP-3.

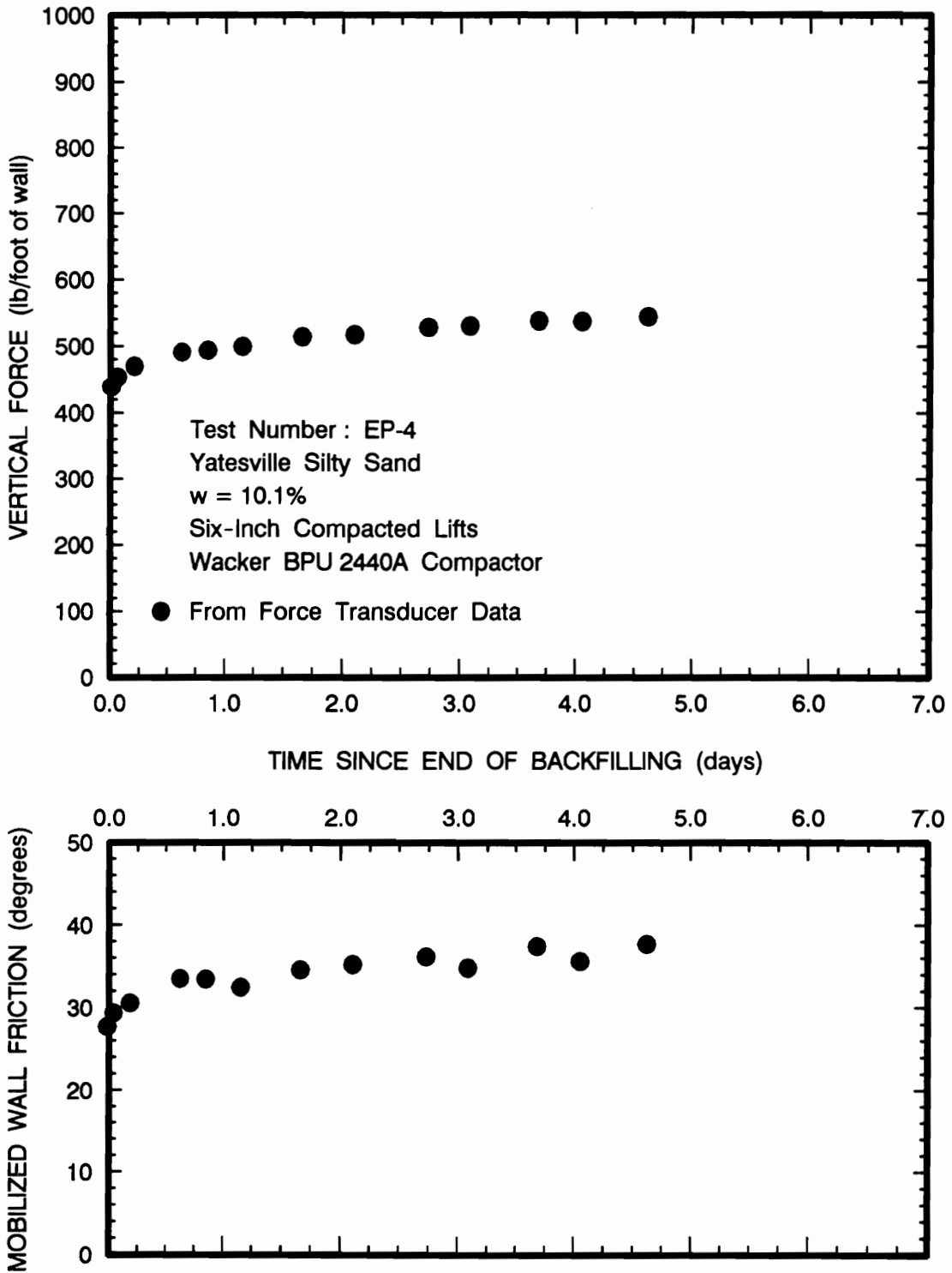


Figure 6.30) Vertical Shear Force and Mobilized Wall Friction as Functions of Time for Test EP-4.

of the mobilized wall friction is primarily the result of a decrease in the lateral pressure and is actually accompanied by a nearly constant vertical shear force.

The amount of published experimental data on soil-wall interface shear forces and values of the mobilized wall friction angle is very limited. The after construction values of the mobilized wall friction angle obtained during this study are in general agreement with the values ranging from 22 to 40 degrees reported by Vogt, et al. (1986) from a large-scale field study.

6.4.6 Earth Pressure Distribution

The lateral earth pressures were recorded using commercially available earth pressure cells. A total of seventeen pressure cells were used to record the earth pressures before and after the compaction of each layer of backfill. The resultant horizontal force represented by the earth pressure, as interpreted from the pressure cell data, has been compared to the total horizontal force for the two panels containing the earth pressure cells. This comparison showed that the two groups of data were generally in agreement with respect to the magnitude of the horizontal force resultant and its point of application.

The agreement between the two groups of data increases the confidence in the accuracy of the individual earth pressure measurements even though the measured values at the same depth or adjacent depths may be significantly different. The variability seen in the earth pressure measurements of this study has also been reported by a number of other

researchers (Goldbeck, 1938; Wright, et al., 1975; Spangler and Mickle, 1956; Rehnman and Broms, 1972; Bruner, et al., 1983; and Vogt, et al., 1986).

The earth pressure cell readings at the end of construction for tests EP-2 through EP-4 are shown in Figures 6.31 through 6.33 as a function of depth below the surface of the fill. A comparison of the data from tests EP-2 and EP-3 indicates that the lateral earth pressures for test EP-2, with a four-inch compacted lift thickness, are approximately twice as high as those for test EP-3, with a six-inch compacted lift thickness. The pressures measured at the end of construction for tests EP-3 and EP-4 are very similar.

6.4.6.1 Time Dependence of the Earth Pressure Distribution

The earth pressure cells were monitored for about five days after the end of construction for tests EP-2 through EP-4. Readings of the pressure cells were recorded at two- to four-hour intervals for the remainder of the day of construction and at about twelve-hour intervals after that. Earth pressure readings after construction were more widely scattered than those obtained during construction. At most of the time intervals, some of the earth pressure cells indicated pressures higher than those after construction while others indicated lower pressures. The range of measured pressures increased with time after construction and in some cases negative pressures were recorded.

The pressures recorded at about 40 hours after construction for tests EP-2 through EP-4 are shown in Figures 6.34 through 6.36 along

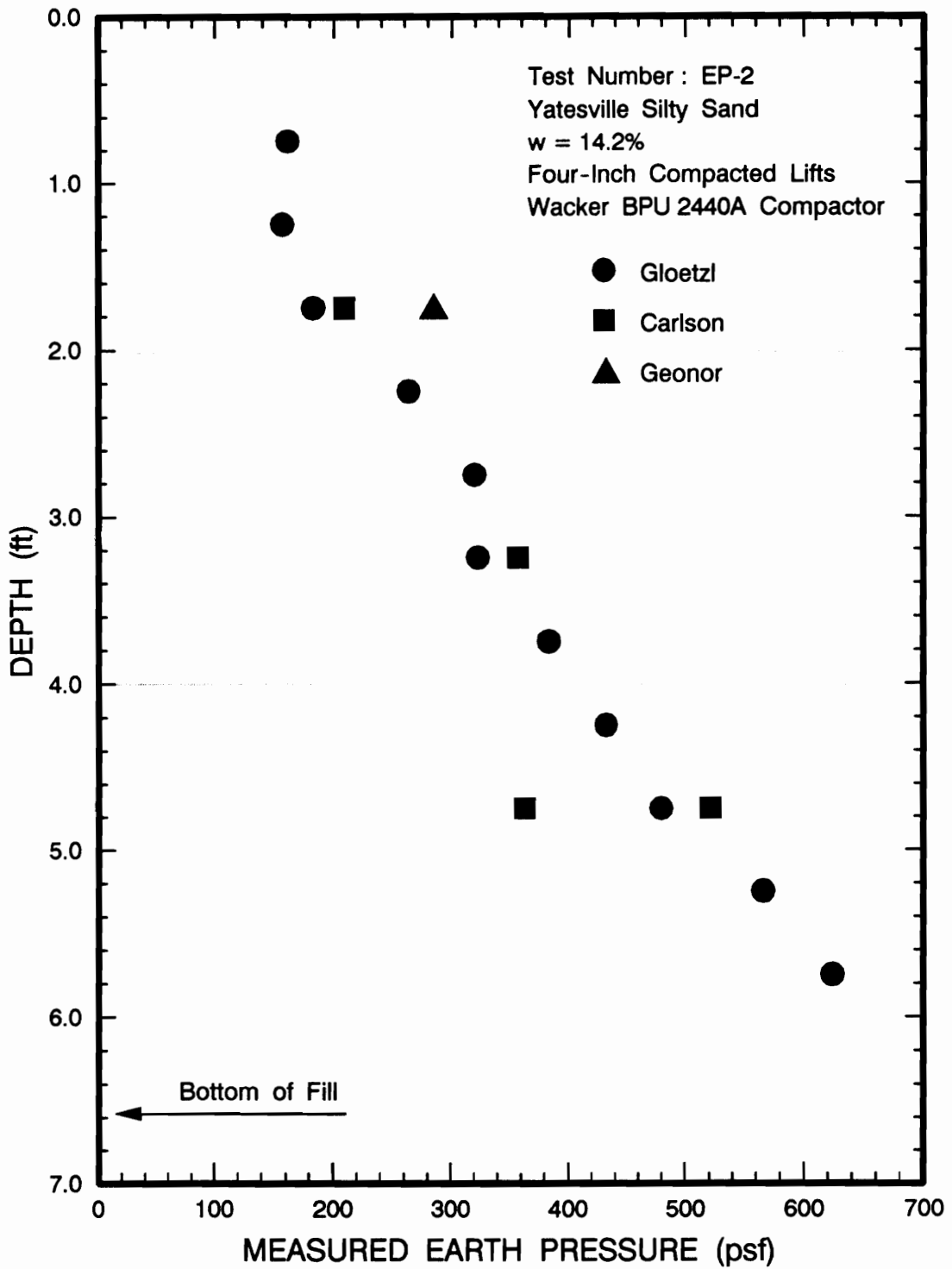


Figure 6.31) Measured Horizontal Earth Pressures at the End of Construction for Test EP-2.

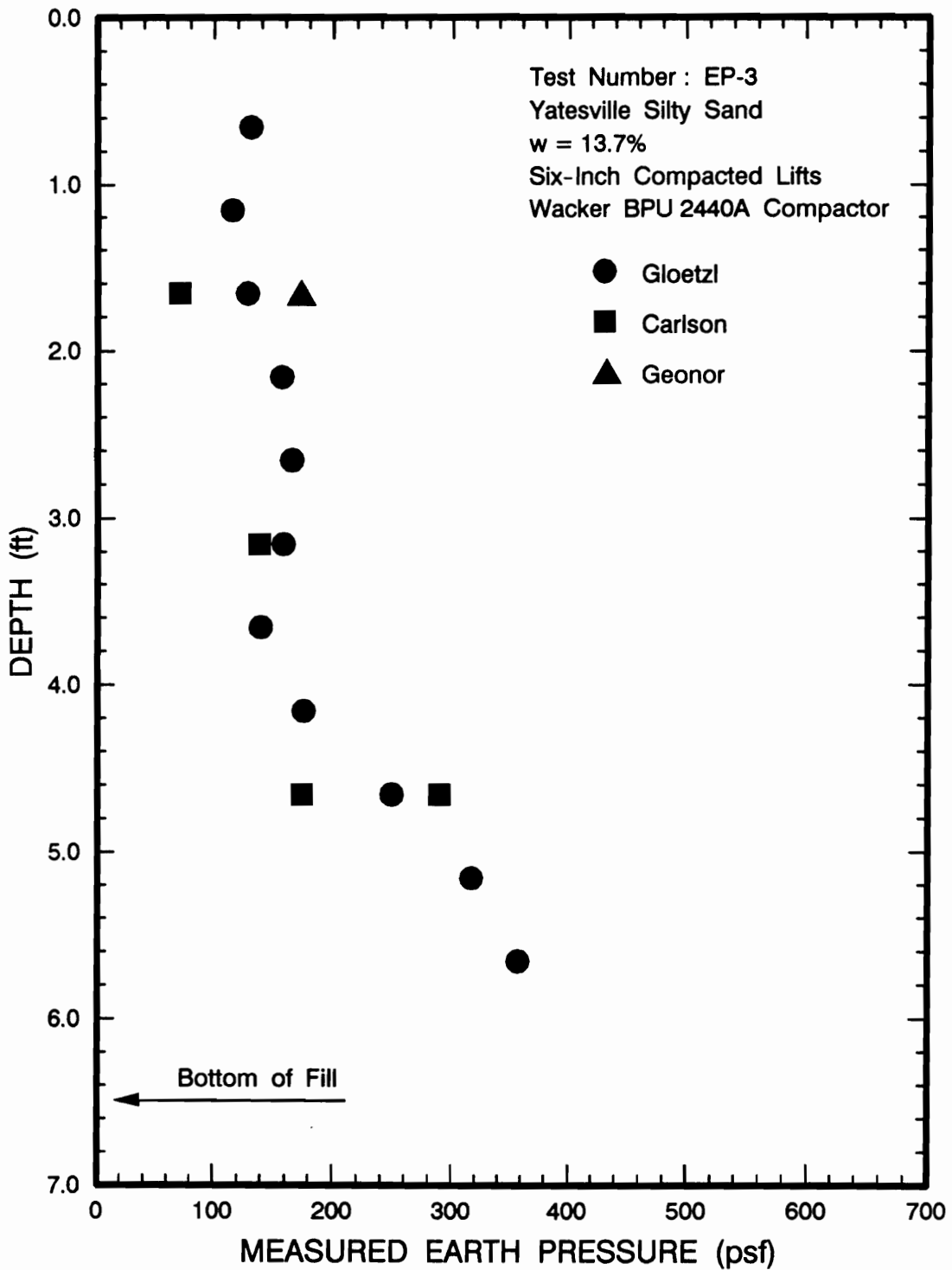


Figure 6.32) Measured Horizontal Earth Pressures at the End of Construction for Test EP-3.

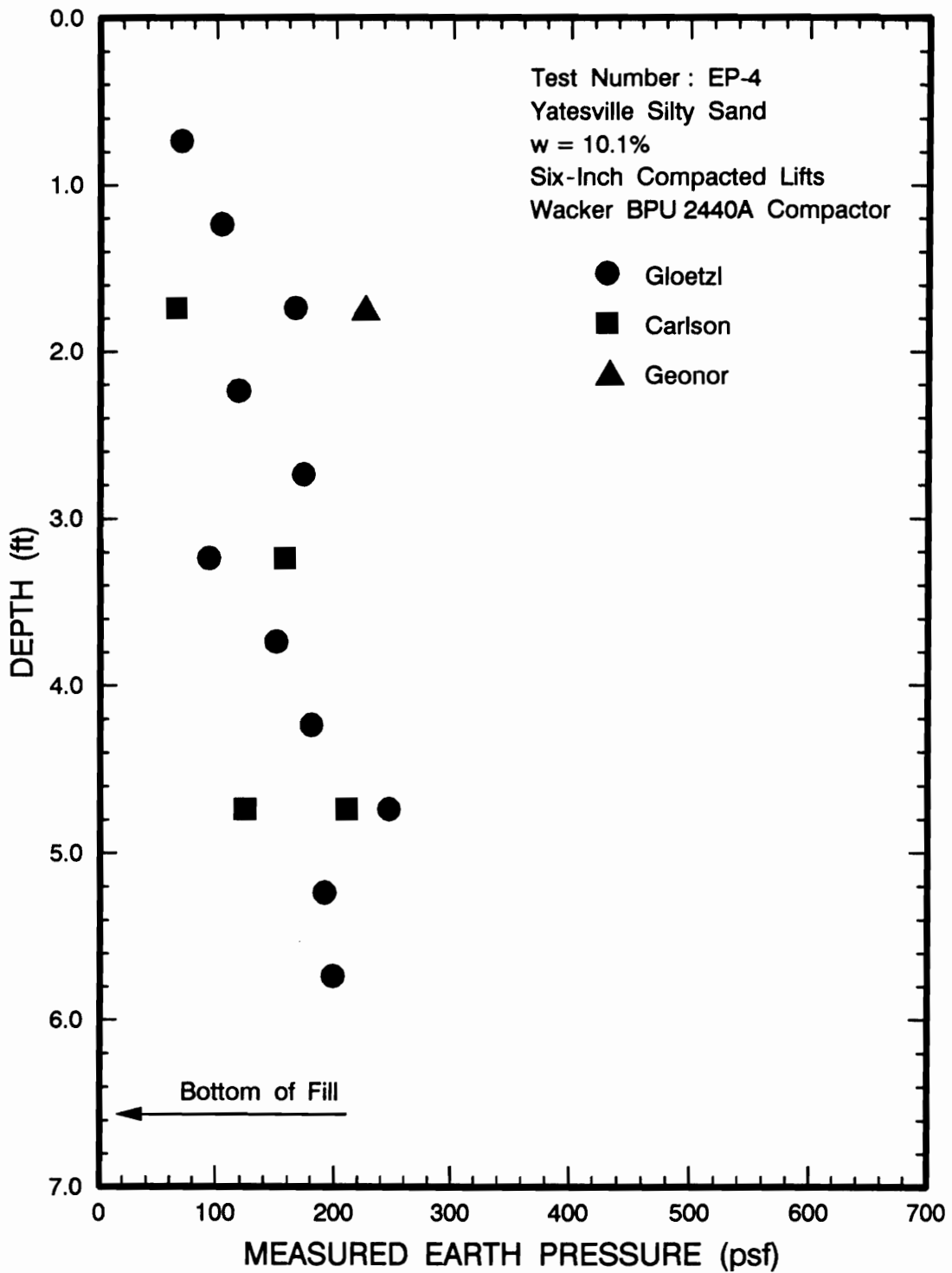


Figure 6.33) Measured Horizontal Earth Pressures at the End of Construction for Test EP-4.

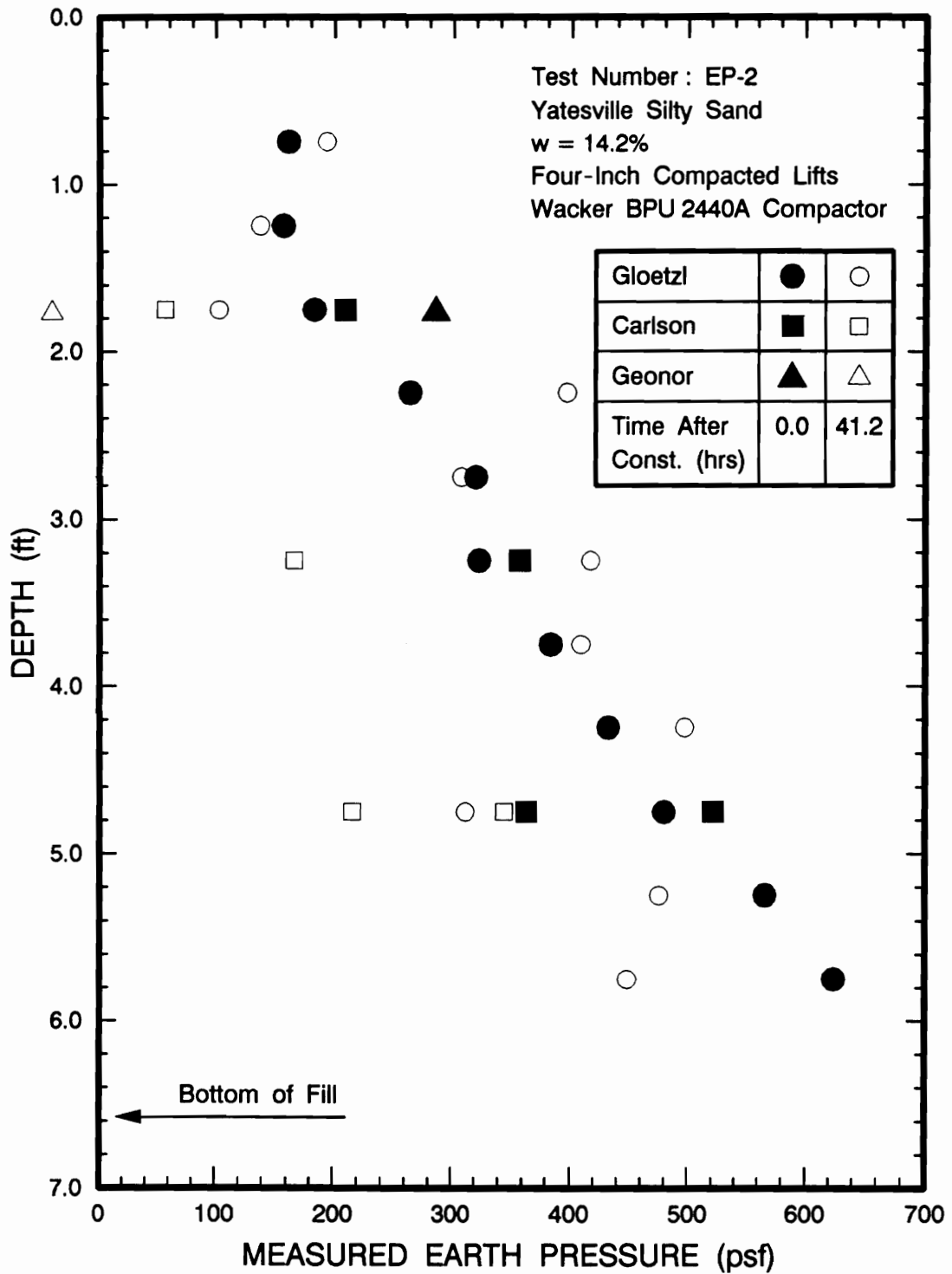


Figure 6.34) Measured Horizontal Earth Pressures at the End of Construction and 41.2 Hours Later for Test EP-2.

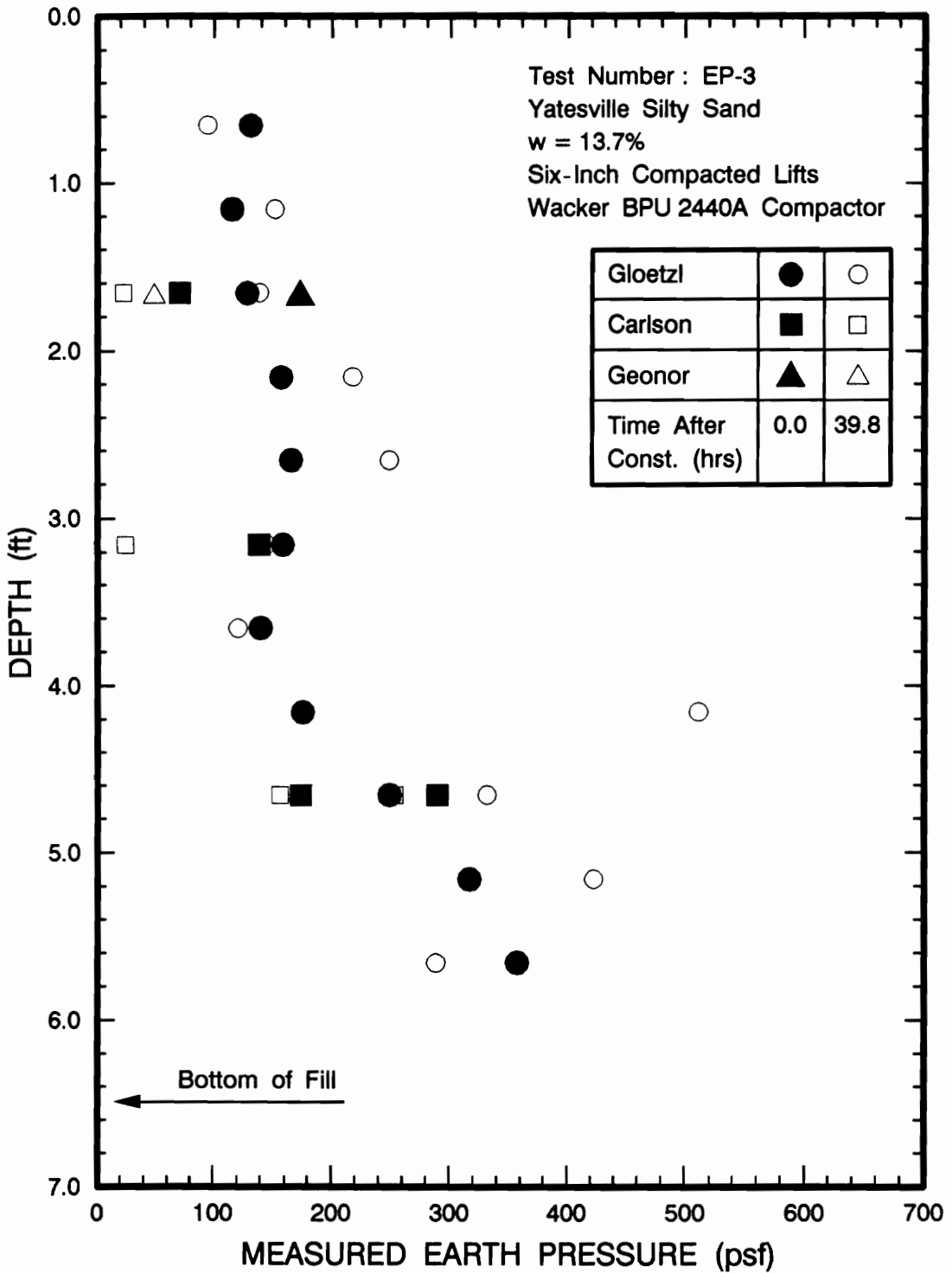


Figure 6.35) Measured Horizontal Earth Pressures at the End of Construction and 39.8 Hours Later for Test EP-3.

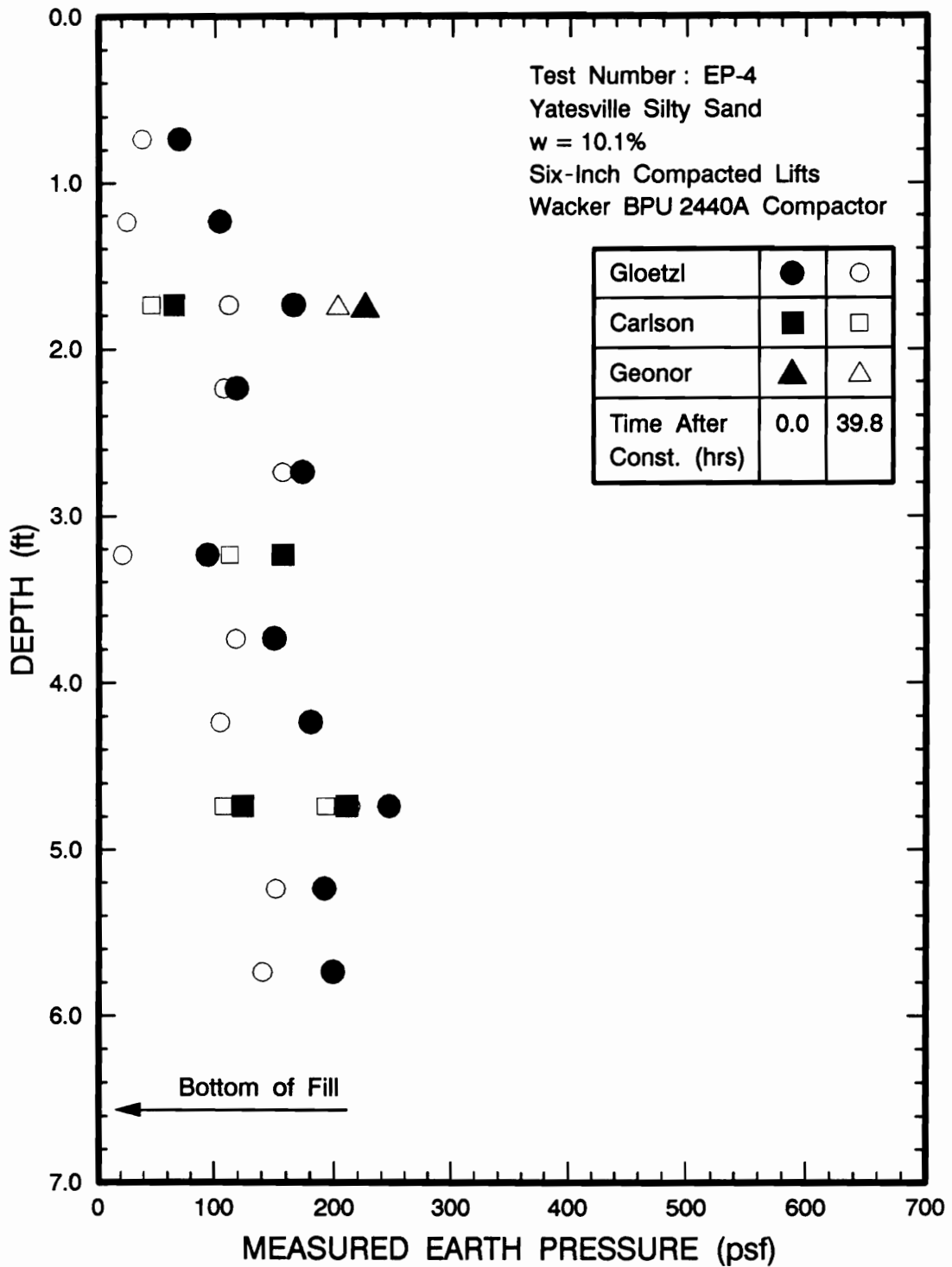


Figure 6.36) Measured Horizontal Earth Pressures at the End of Construction and 39.8 Hours Later for Test EP-4.

with the pressures recorded at the end of construction. The earth pressures at the end of construction are represented by the solid symbols and those at about forty hours after construction are represented by the open symbols. The irregularity of the magnitude and direction of the pressure changes in these figures is typical of that observed for the other time intervals. The data in Figure 6.36 for test EP-4 indicate a consistent trend in that each pressure cell registered a lower pressure forty hours after construction than at the end of construction. This consistency was not noticed for all of the time intervals of test EP-4 but in general the pressure recorded for test EP-4 were more uniform with time than those recorded for tests EP-2 and EP-3.

The reason for the wide variation of pressures measured after construction is not clear but is probably influenced by a number of factors including:

- 1) Redistribution of locally high or low pressures produced by compacting the backfill in layers.
- 2) Time-dependent behavior of the backfill material.
- 3) Redistribution of excess pore pressures caused by compaction.
- 4) Time- and/or temperature-dependent response of the earth pressure cells.
- 5) Time- and/or temperature-dependent characteristics of the data-acquisition system.

Effects of items 1 through 3 represent characteristics of the backfill-wall system and require additional study before they can be

properly evaluated. Items 4 and 5 represent two of several possible system problems that can introduce errors into the recorder pressures. These and other potential sources of error need to be investigated and, if they exist, steps should be taken to minimize their effects.

6.5 COMPARISONS BETWEEN MEASURED AND PREDICTED HORIZONTAL EARTH PRESSURES

The after-compaction earth pressure versus depth profiles were calculated for the conditions of tests EP-2 through EP-4 using the method developed by Seed and Duncan (1983). The analyses were performed using the computer program ECOMPAC developed by Duncan, et al. (1989) which utilizes a revised form of the computer program NCOMP developed by Seed and Duncan (1983).

The test conditions analyzed and the soil parameters and compactor characteristics used during the analyses are listed in Table 6.3. The layer thicknesses and number of layers are those used for each of the tests. The unit weights and moisture contents were determined from sand cone density tests performed at the time of construction of the backfill. The soil strength parameters c and ϕ are based on the results of unconsolidated undrained triaxial testing of the compacted backfill. Values for Poisson's ratio, α , and $K_{1,\phi}$ are determined by the program ECOMPAC based on the friction angle, ϕ , of the backfill. The parameter β is taken as 0.60 based on the suggestion by Seed and Duncan (1983). The compactor plate dimensions are those of the Wacker BPU 2440 A used during this study.

Table 6.3) Test Conditions and Soil Parameters for the Analytical Studies.

	TEST NUMBER		
	EP-2	EP-3	EP-4
Compacted Layer Thickness (in.)	4	6	6
Number of Layers	20	13	13
Dry Unit Weight, γ_d (lb/ft ³)	119	120	106
Water Content, w (percent)	14.2	13.7	10.1
Total Unit Weight, γ_m (lb/ft ³)	136	136	117
Undrained Cohesion, c (lb/ft ²)	910	300	360
Total Stress Friction Angle, ϕ	29°	34°	28°
At-Rest Earth Pressure Coeff., K_0	0.75	0.40	0.35
Poisson's Ratio	0.42	0.40	0.42
α	0.47	0.60	0.45
β	0.60	0.60	0.60
$K_{1,\phi}$	2.88	3.54	2.77
Total Compactor Load (pounds)	2000	2000	2000
Compactor Plate Dimensions, (L x W, in. x in.)	20.0 x 15.5	20.0 x 15.5	20.0 x 15.5

The effect of the vibrating compactor on the lateral stresses in the backfill is modeled based on the peak lateral pressure produced by a total compactor load. The total compactor load represents the static weight of the compactor plus an additional weight used to represent the dynamic force of the compactor. According to the manufacturer's literature, the dynamic force for the Wacker BPU 2440 A compactor used in this study is 5400 pounds and the static weight is 267 pounds.

For large vibrating rollers, data reported by D'Appolonia, et al. (1969), Whiffen (1953), and Toombs (1972) indicate that large vibratory compactors induce peak earth pressures corresponding to a static load equal to about 2 to 3 times the weight of the compactors. Based on comparisons between analytical studies and field measurements, Seed and Duncan (1986) suggested that for small vibratory compactors the total compactor load used to represent a vibratory compactor may be as high as 10.2 to 12.4 times its static weight. The total compactor load of 2000 pounds used to represent the Wacker BPU 2440 A vibratory plate compactor corresponds to 7.5 times its static weight. Due to the lack of available information on which to base the value of the total compactor load, the value of 2000 was selected because it produced good agreement between the analytical predictions and the field data, and because it is within the range of expected values as discussed above.

The agreement between the earth pressures measured at the end of construction and those calculated using the method of Seed and Duncan (1986) is illustrated in Figures 6-37 through 6-39 for tests EP-2 through EP-4. The shape of the upper portion of the predicted lateral

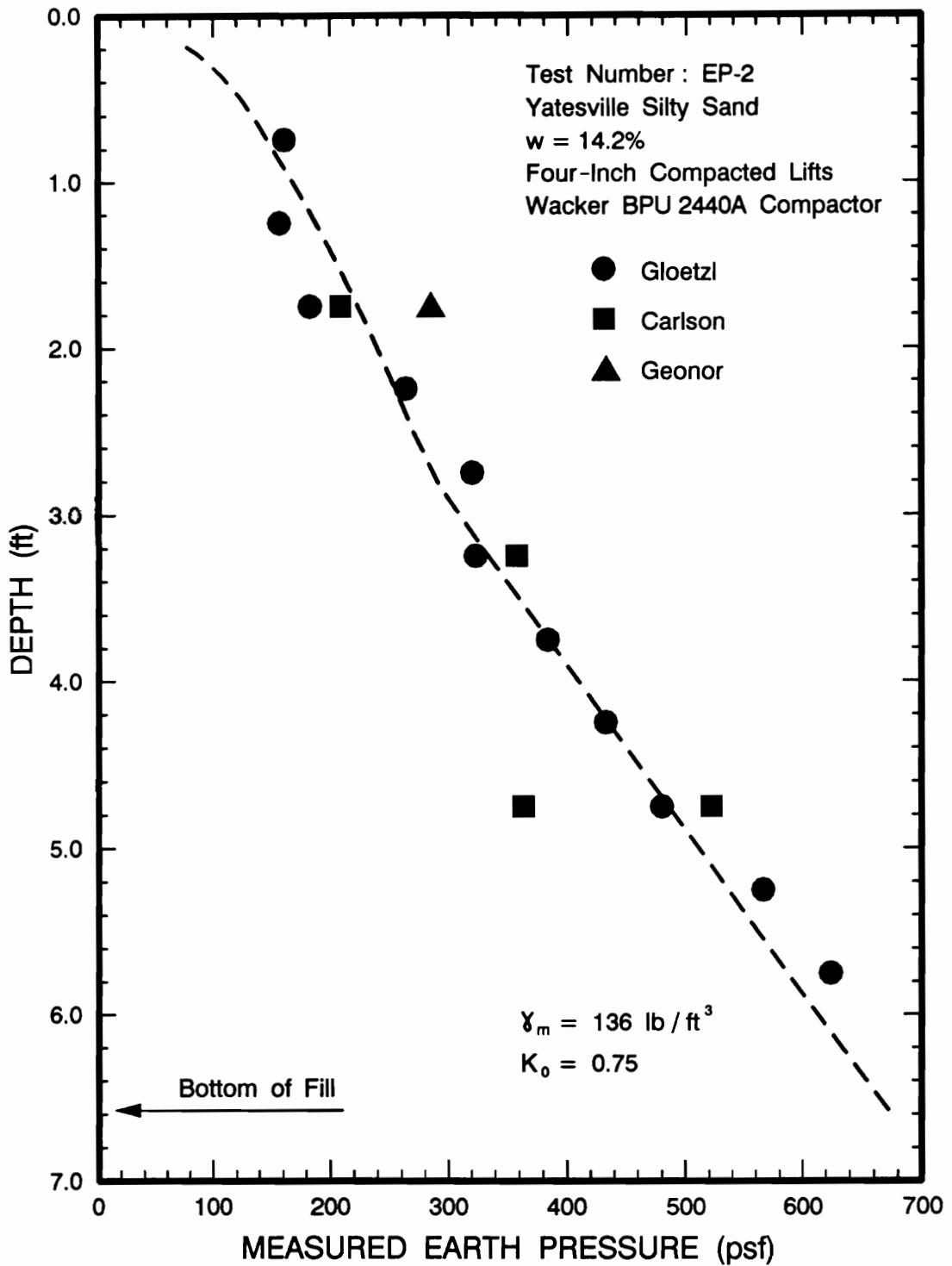


Figure 6.37) Comparison Between Measured and Predicted Horizontal Earth Pressures at the End of Construction for Test EP-2.

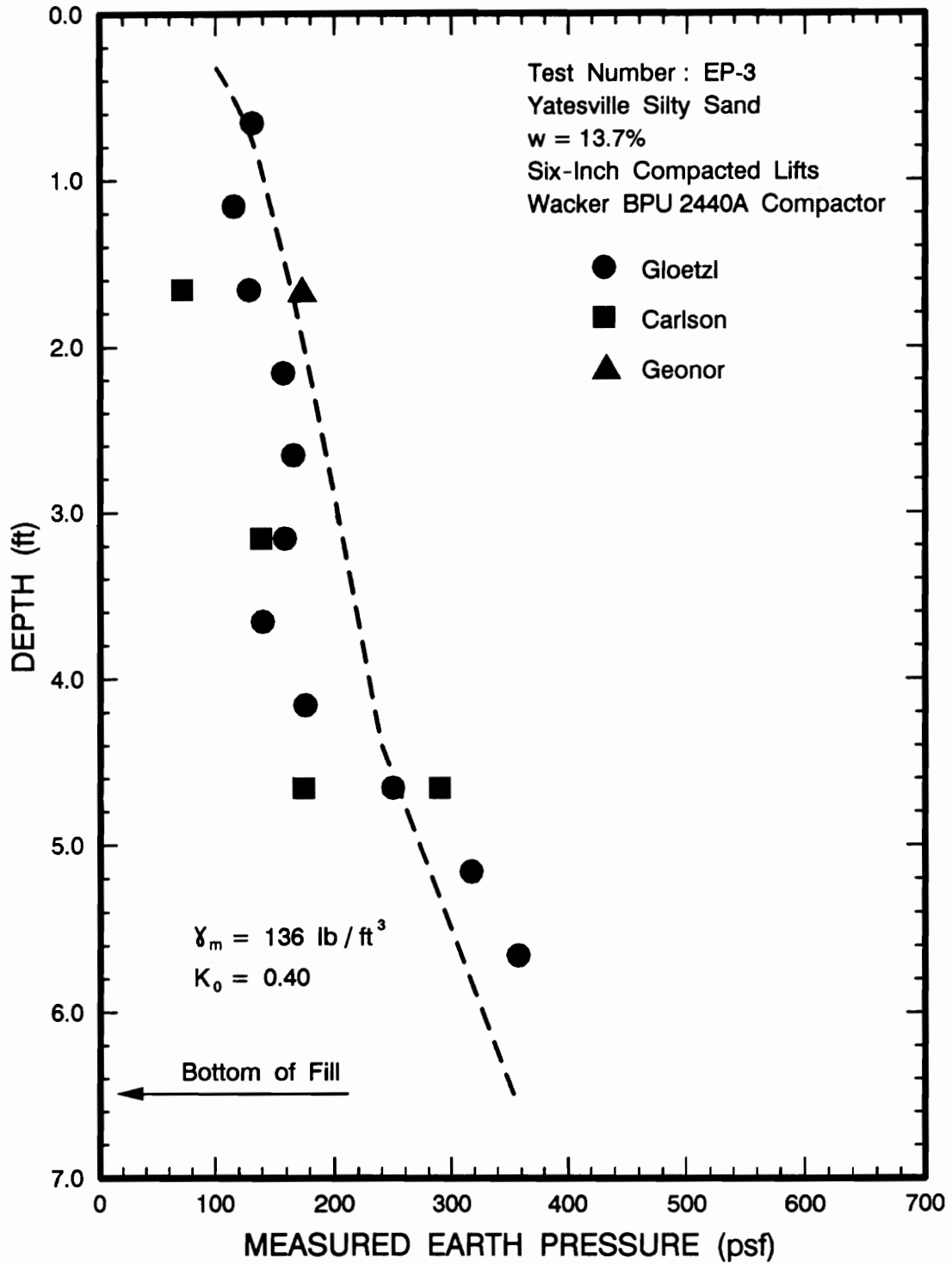


Figure 6.38) Comparison Between Measured and Predicted Horizontal Earth Pressures at the End of Construction for Test EP-3.

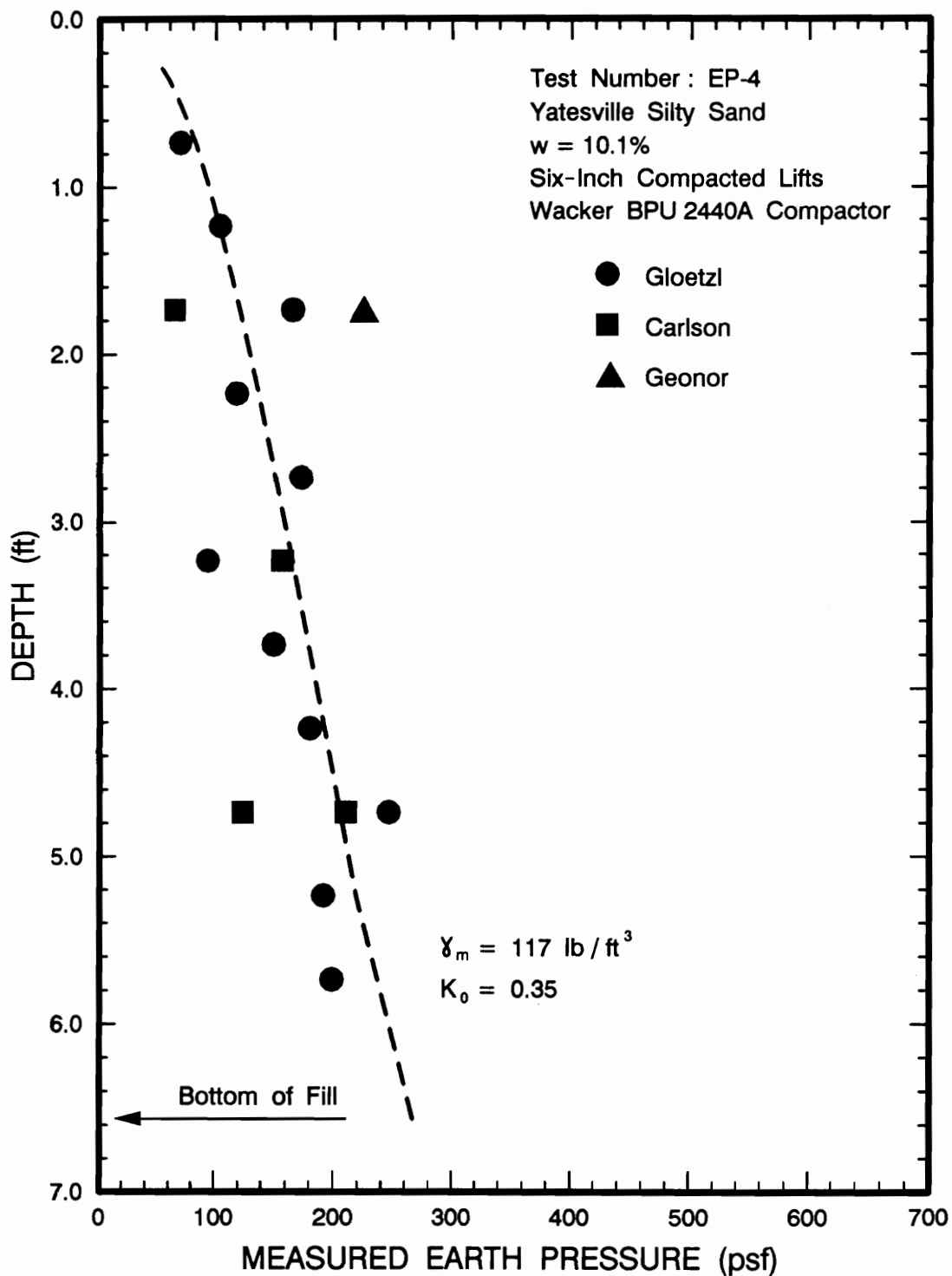


Figure 6.39) Comparison Between Measured and Predicted Horizontal Earth Pressures at the End of Construction for Test EP-4.

earth pressure versus depth relationship is primarily a function of the soil strength parameters and the peak lateral pressures induced by the compactor. Therefore, the value selected for the total compactor force will influence the predicted earth pressures in the upper layers of the backfill. For each of the three tests, the lower portion of the predicted earth pressure profile indicates a linear increase in pressure with depth. The start of this linear variation is at a depth below which the compaction-induced horizontal pressures are exceeded by the at-rest horizontal pressures calculated as:

$$\sigma_h' = K_0 \sigma_v' = K_0 \gamma z \quad \text{Eqn. 6.1}$$

where: σ_h' = horizontal effective stress,
 σ_v' = vertical effective stress,
 K_0 = at-rest earth pressure coefficient,
 γ = unit weight of the soil, and
 z = depth.

The slope and position of this straight line portion of the predicted pressure profile are controlled by the values of γ and K_0 used in the analyses. As stated earlier, the values used for γ in the analyses were based on tests performed at the time of backfilling. The values of K_0 were chosen to provide the best agreement between the predicted and observed lateral earth pressure profiles. The values of K_0 used in the analyses were: $K_0 = 0.75$ for test EP-2, $K_0 = 0.40$ for test EP-3, and $K_0 = 0.35$ for test EP-4.

The K_0 value of 0.75 required to produce the agreement between the measured and predicted lateral pressure profiles for test EP-2 seen in Figure 6.37 seems unrealistically high. The agreement between the measured and predicted lateral pressure profiles for this test will be greatly reduced if a more reasonable value of K_0 is used. This is particularly true for the pressures in the lower portion of the backfill.

The difficulty in modeling the measured compaction-induced lateral earth pressures of test EP-2 with the procedure of Seed and Duncan (1983) may be caused by several factors:

- 1) Three sand-cone density tests on the compacted backfill indicated 93, 94, and 99 percent saturation. This high degree of saturation coupled with densification due to the increasing vertical pressure as a result of the placement of additional layers of backfill may have led to a fully saturated condition in the lower portions of the backfill. As a result, the changes in total lateral pressure may have been nearly equal to the changes in total vertical pressure produced by additional layers of backfill.
- 2) The earth pressure cell data and the horizontal-force transducer data represent total stress measurements.
- 3) The permeability of the compacted backfill may have been low enough to allow significant pore pressures to developed during construction. These pore pressures would influence the behavior of the backfill and the observed horizontal earth pressures.

- 4) The effects of pore pressures cannot be readily assessed because the method of analysis does not account for pore pressures and pore pressure measurements were not made.
- 5) The efficiency of the compactor may depend on the soil properties and the use of a total compactor force of 2000 pounds may be inaccurate for the conditions of test EP-2.

For tests EP-3 and EP-4 the K_0 values used in the analyses were 0.40 and 0.35, respectively. These values, although slightly low, seem reasonable for a compacted backfill. The use of a 2000-pound total compactor force to represent the Wacker BPU 2440A vibratory compactor seems justified by the fact that, for all three tests, it produced good agreement between the measured and predicted lateral earth pressures in the upper portion of the backfill where lateral pressures are directly affected by the total compactor force.

Based on the reasonableness of the K_0 values and the 2000-pound total compactor force used to analyze tests EP-3 and EP-4, the method of evaluating compaction-induced lateral earth pressures presented by Seed and Duncan (1986) produces results that are in good agreement with the end of construction earth pressures determined by experiment for the conditions of tests EP-3 and EP-4. This agreement is illustrated by Figures 6-38 and 6-39 and is summarized in Table 6.4 in terms of the horizontal force resultant and its point of application as calculated from the measured and predicted values.

In general, the agreement between the shapes of the experimental and predicted earth pressure profiles at the end of construction and the

Table 6.4) Summary of Comparisons Between the Measured and Calculated Values of the Magnitude and Location of the Horizontal Earth Pressure Force Resultant.

	Horizontal Force Resultant (lb/ft of wall)	Location of Force Resultant h/D
TEST NUMBER EP-2		
Load Cell Data at End of Const.	2030	0.36
Earth Pressure Cell Data at End of Const.	2401	0.37
Predicted by Analytical Method	2330	0.37
TEST NUMBER EP-3		
Load Cell Data at End of Const.	1110	0.37
Earth Pressure Cell Data at End of Const.	1300	0.39
Predicted by Analytical Method	1380	0.41
TEST NUMBER EP-4		
Load Cell Data at End of Const.	830	0.45
Earth Pressure Cell Data at End of Const.	980	0.42
Predicted by Analytical Method	1040	0.39

agreement between the measured and predicted horizontal force resultant and its point of application are encouraging. Further comparisons between results from the Instrumented Retaining Wall Facility and the analytical method of Seed and Duncan (1986) are needed to substantiate this agreement and to guide future developments of the analytical method.

6.6 COMPARISONS BETWEEN MEASURED AND PREDICTED VERTICAL SHEAR FORCES

Based on a number of finite element studies of 40-foot-high retaining walls, Ebling, et al. (1989) found that the vertical shear force acting on a retaining structure is related to the depth and unit weight of the backfill and can be approximated as:

$$V = 0.5 K_v \gamma H^2$$

where : V = vertical shear force per linear foot of wall,

K_v = vertical shear coefficient,

γ = unit weight of the soil, and

H = depth of backfill.

Based on the finite element analyses, the value of the vertical shear coefficient is not less than about 0.1 for a wide range of conditions of wall geometry and backfill properties.

Figures 6.40 through 6.42 compare the values predicted by the above equation, using $K_v = 0.1$, with the values measured during tests EP-2 through EP-4. The measured values represent the average vertical shear forces on Panels 2 and 3. With the exception of the shallow backfill

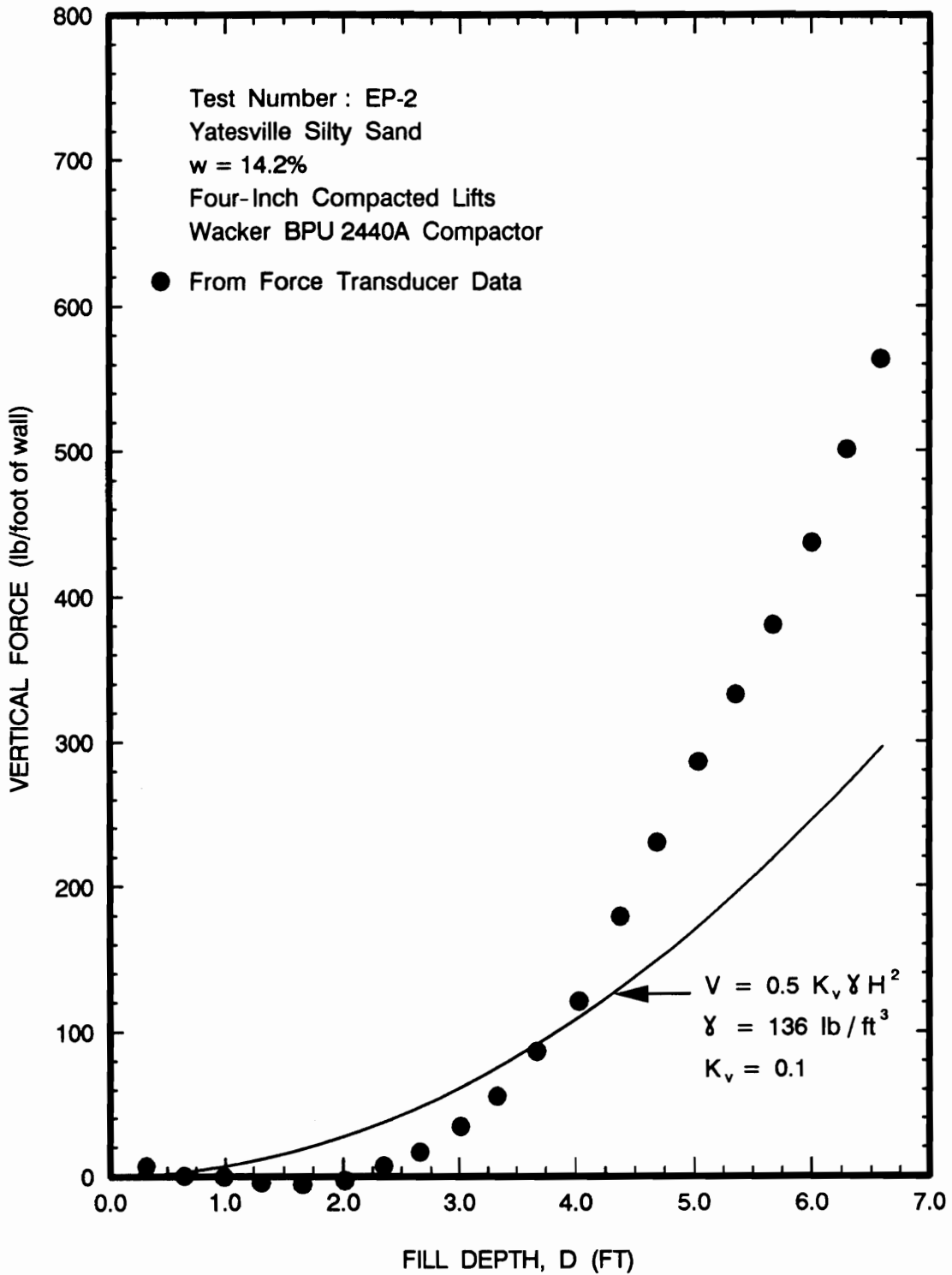


Figure 6.40) Comparison Between the Measured and Predicted Vertical Shear Force During Construction for Test EP-2.

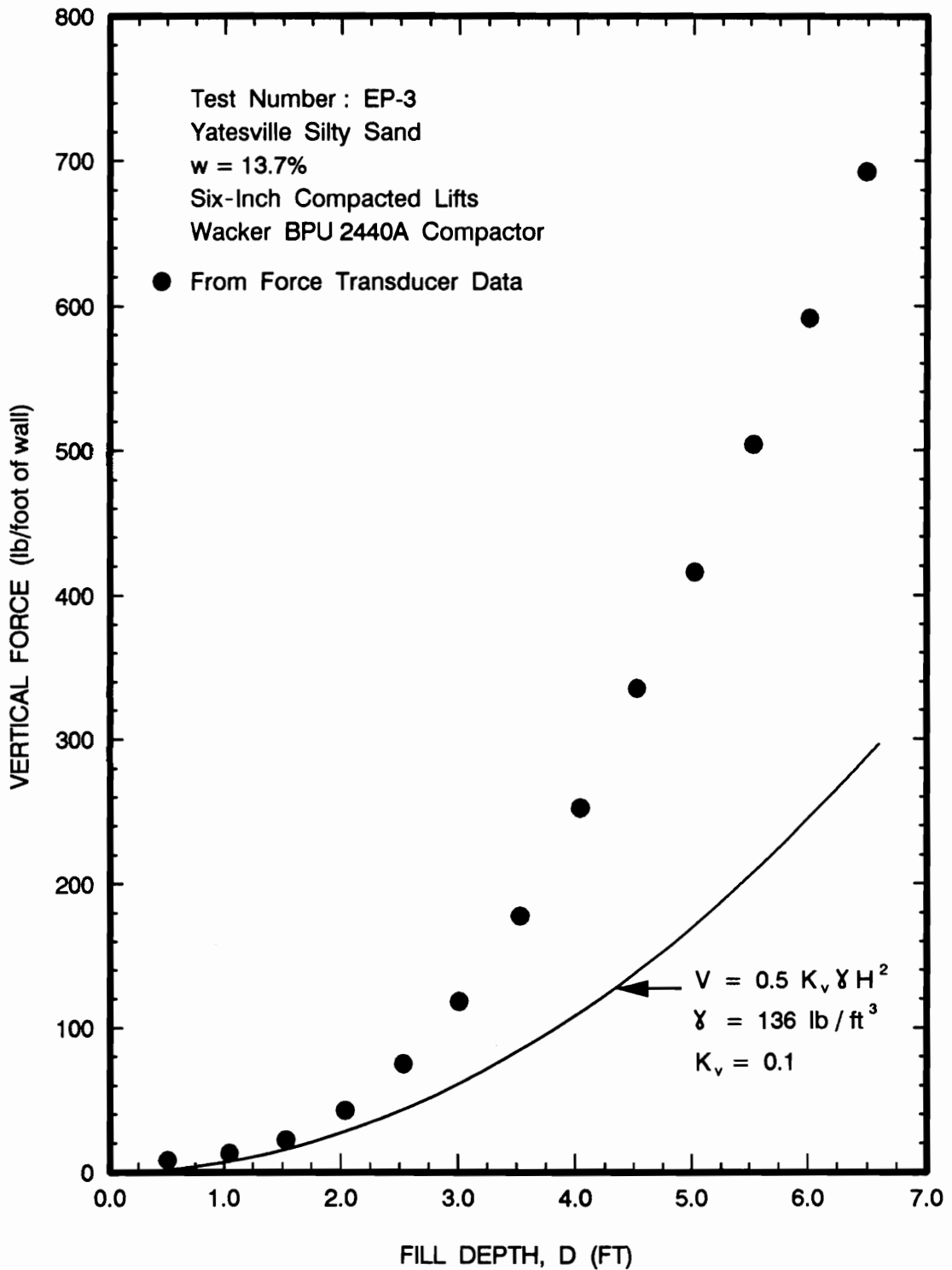


Figure 6.41) Comparison Between the Measured and Predicted Vertical Shear Force During Construction for Test EP-3.

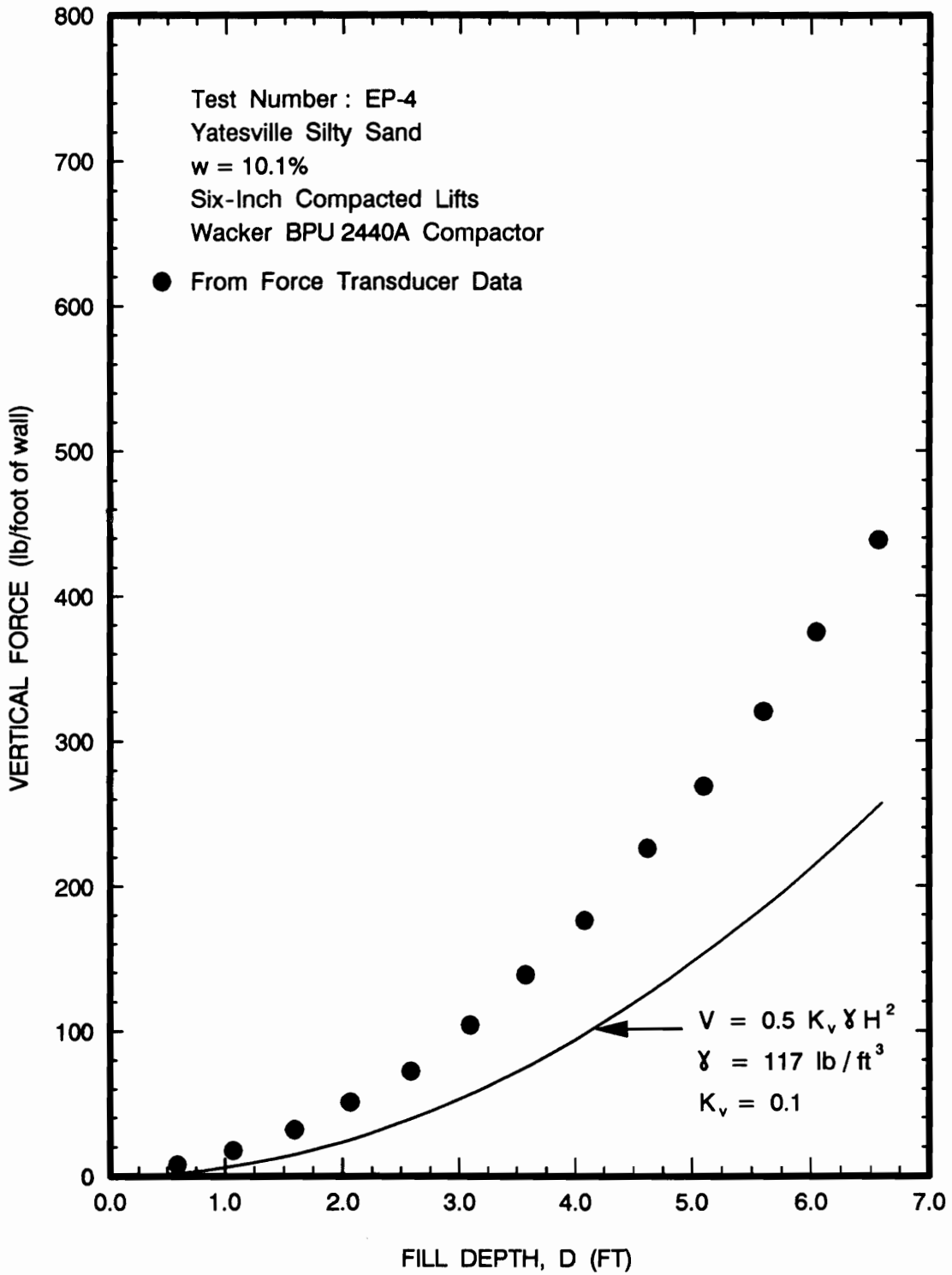


Figure 6.42) Comparison Between the Measured and Predicted Vertical Shear Force During Construction for Test EP-4.

depths for test EP-2, the equation tends to underestimate the measured shear forces. At the end of construction, the predicted values were about 40 to 60 percent of the measured values.

6.7 SUMMARY

The Instrumented Retaining Wall Facility was used to investigate the horizontal and vertical forces exerted on retaining structures. Four tests were performed by compacting Yatesville silty sand behind the ten-foot-long by seven-foot-high instrumented wall. The backfills were compacted in layers using a Wacker BPU 2440 A vibratory plate compactor, with compacted lift thicknesses of four inches and six inches. The water content of the compacted fills ranged from about two percent wet of optimum to about two percent dry of optimum with the optimum water content being 12.5 percent, based on the standard Proctor compaction effort. During each test, measurements were recorded before and after compaction of each lift and periodically after construction for a period of about five days. The measured values included: 1) horizontal earth pressures, 2) horizontal reaction forces, 3) vertical reaction forces, 4) wall displacements, 5) backfill depths, 6) temperatures, and 7) time.

The results of the first four tests indicated that:

- 1) The instrumented wall system is relatively stiff and wall displacements are small enough to allow the accurate measurement of compaction-induced earth pressures. The maximum recorded horizontal wall displacements corresponded to no more than twenty percent of the value recorded by Terzaghi (1934a) as required to produce the

minimum lateral pressure for a compacted backfill. Typical displacements were considerably less than the maximum.

- 2) The horizontal and vertical forces varied considerably among the four wall panels. This is believed to be the result of operating the Bobcat loader on the backfill next to Panels 3 and 4, and not operating it next to the other two panels. The earth pressures exerted on Panel 1 were probably affected by the boundary condition imposed by the end wall of the test facility.
- 3) Comparisons between the total horizontal force and its point of application, interpreted from the horizontal-force transducers and from the earth pressure cell data, indicate good agreement between these two measuring systems during backfilling.
- 4) For tests EP-2 and EP-3, the agreement between the total horizontal force and its point of application calculated from the horizontal force transducer data and those calculated from the earth pressure cell data began to deteriorate shortly after construction.
- 5) The mobilized wall friction angles during and after construction were within the range of values reported by Vogt, et al. (1986) for a compacted backfill.
- 6) Vertical shear forces recorded during the four- to five-day observation period after construction were as high or higher than those recorded during construction. For test EP-2 the vertical shear force increased 42 percent above the end of construction value within about two days after construction.

- 7) For tests EP-3 and EP-4 the earth pressure profiles at the end of construction agreed well with those predicted by the analytical method presented by Seed and Duncan (1986).
- 8) Agreement between the measured earth pressure profile for test EP-2 and that predicted by the analytical method could not be achieved unless the relatively high K_0 value of 0.75 was used.
- 9) Pore water pressures are likely to affect the behavior of the backfill and the horizontal and vertical forces exerted on the wall.
- 10) The scatter of the values of the measured horizontal earth pressures generally increased with time after construction and some earth pressure cells indicated negative pressures.

Based on the results of the first four tests using the Instrumented Retaining Wall Facility, it appears to be well suited for investigating horizontal and vertical loads imposed on retaining structures by compacted backfills. Several of the test results indicate that test procedures and instrumentation characteristics may be influencing the measured values. Future testing programs should be designed to reduce or eliminate these concerns.

CHAPTER 7

CONCLUSIONS

The purpose of this study was to develop and validate equipment and procedures suitable for the experimental investigation of earth pressures. The primary objectives were to: 1) review reports of experimental studies of earth pressures on retaining structures, 2) review reports of laboratory studies of the at-rest earth pressure coefficient, 3) review the current methods of analysis for compaction-induced earth pressures, 4) develop and test an instrumented oedometer, 5) develop and test an instrumented retaining wall facility, and 6) compare the experimental results obtained from the new instrumented retaining wall facility to those of earlier studies and to current analytical methods.

7.1 CONCLUSIONS

The following conclusions are based on the findings of this study.

- 1) Several researchers have investigated various aspects of the interaction between retaining structures and their backfills. The usefulness of earlier studies for developing a clear understanding of the factors effecting the earth pressures on structures is often limited by the lack of detail with regard to soil properties, test equipment, test procedures, and instrumentation methods. In most of the earlier studies, only a small number of tests were performed using a particular test facility. This makes comparisons between the

studies difficult. Reports of field instrumentation projects are potentially very important because they provide the closest representation of the real project. However, the number of variables is usually higher for field studies than for laboratory studies and the researcher(s) may have limited control over the construction procedures. This makes interpretation of field measurements particularly difficult.

- 2) The instrumented oedometer developed during this study provides a convenient and reliable method of determining the effect of number of load cycles on the value of the lateral earth pressure coefficient. Tests performed on Monterey sand #0/30 using 1000 load cycles indicated that for relative densities between 75 and 85 percent there was little effect on the value of K_0 at an OCR of 1.0. At an OCR of 10.0, the 1000 load cycles produced an increase in K_0 ranging from 9 to 30 percent.
- 3) The Instrumented Retaining Wall Facility developed during this study was designed to allow repeated testing of different soil types using different test procedures. This allows the researcher(s) to carefully control many of the factors that influence the earth pressures on retaining structures and to evaluate the significance of each. The facility is large enough to accommodate the smaller compactors used in the construction industry and to allow a front-end loader to be used to assist with the placement and removal of the backfill. All measurements are recorded using a microcomputer-based data-acquisition system. With this facility, a 6.5-ft.-deep backfill

can be constructed in one day. This includes placing and compacting about 24 cubic yards of soil in six-inch lifts and recording more than sixty measurements before and after the compaction of each lift.

- 4) Horizontal wall displacements measured during the first four earth pressure tests using Yatesville silty sand indicated that the wall stiffness is great enough to allow accurate measurement of compaction-induced lateral earth pressures.
- 5) Comparisons between the horizontal force resultant and its point of application, evaluated from the horizontal force measurements and from the earth pressure cell measurements, indicated the two types of measurements were in good agreement during backfilling. Shortly after backfilling, the agreement between these two measuring systems began to deteriorate.
- 6) The vertical shear forces exerted on the wall at the end of construction corresponded to mobilized wall friction angles ranging from about 15° to about 32° . These values are within the range of values reported by Vogt, et al. (1986).
- 7) Vertical shear forces on the wall panels increased after construction and remained above the end of construction values during the four- to five-day observation period.
- 8) The method of predicting compaction-induced earth pressures presented by Seed and Duncan (1986) produced good agreement with the measured values. However, for the case of test EP-2, where the compaction water content was about two percent wet of optimum, the relatively high value for K_0 of 0.75 was required to match the pressures

measured in the lower portions of the backfill. For this test, the effects of the pore water pressures may have influenced the measured pressures. These effects are not directly accounted for in the analytical method and were not recorded during the tests.

- 9) With time after construction, the scatter in the measured earth pressure values became quite large and some earth pressure cells at shallow depths indicated negative pressures. The reason for this was not clear at the time this study was concluded.

7.2) RECOMMENDATIONS FOR FUTURE RESEARCH

The Instrumented Retaining Wall Facility is a valuable tool for the investigation of a number of areas related to earth-structure interactions. The recommendations for future research presented here will be limited to those related to compaction-induced earth pressures.

The recommendations are:

- 1) A series of tests performed to evaluate the accuracies of the various instrumentation systems as a function of time and as influenced by environmental factors would provide useful information for the evaluation of test results and the formulation of new test procedures.
- 2) For vibratory compactors, additional information is needed to provide a rational method for selecting the total compactor force to be used in the analytical methods. This information should be obtained for several compactors operating on different soil conditions to establish a range of values.

- 3) For moist backfills containing an appreciable amount of fines, the pore fluid pressures during and after compaction are likely to affect the earth pressures. An instrumentation system to monitor pore fluid pressures in the partially saturated backfill would provide valuable information for these backfill conditions.
- 4) Tests using a variety of compaction water contents, soil types, compactor types and sizes, and lift thicknesses would provide valuable information for further validation and improvement of the analytical methods.

The instrumented oedometer provides a convenient means of performing multi-cycle K_0 tests. A series of tests performed on several soil types at several water contents would provide data for comparison with the multi-cycle K_0 -loading/unloading model proposed by Seed and Duncan (1986). As in the case of 3) above, the implementation of a scheme to monitor the pore fluid pressures would provide useful information.

For both of the testing systems developed during this study, as with all experimental equipment, it is important to periodically check the equipment calibrations and verify that all systems are operating correctly and producing accurate information. Continued use of these systems will undoubtedly lead to future developments that will increase their accuracy and usefulness and produce the needed experimental data.

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APPENDIX A
TEST CONTROL AND DATA-ACQUISITION COMPUTER PROGRAM
FOR THE INSTRUMENTED OEDOMETER

A.1 INTRODUCTION

KOPAR.BAS is a test control and data acquisition program that is used with the instrumented oedometer. The instrumented oedometer is used to investigate the relationship between the vertical and horizontal stresses of a soil. The program controls the vertical pressure and records the measurements during a test.

At the start of each test, the test operator defines the desired load sequence by responding to a series of prompts generated by the program. After this information has been entered and the system zero readings have been recorded, the test procedure is controlled by the program through the interfacing hardware. Instrument readings are recorded for each pressure increment and stored on the computers hard disk drive. The data file is periodically copied to a floppy disk in drive A, enabling the test operator to utilize the information before the test has been completed.

The program is written in Microsoft QuickBasic and utilizes library functions provided by MetraByte Corporation to address the MetraByte data-acquisition hardware. The QuickBasic program KOPAR.BAS consists of a main program and fifteen sub programs. The following sections contain

a brief description of the function of each program segment and a listing of the program.

A.2 FUNCTION OF PROGRAM SEGMENTS

- 1) Main program KOPAR.BAS declares the subroutines, dimensions the array variables, initializes variables, prompts the user to define the desired loading sequence, and calls the various subroutines to produce the defined load sequence and record the data.
- 2) Subprogram ALARM produces an alarm sound from the speaker on the computer.
- 3) Subprogram ANYKEY delays the program until one of the keyboard keys is pressed.
- 4) Subprogram ERRORCODES prints an error message on the screen if an error is encountered during a library call to the data-acquisition hardware.
- 5) Subprogram INITDAS8 initializes the MetraByte DAS-8 data-acquisition hardware.
- 6) Subprogram LOOPS generates the specified number of load/unload cycles by incrementally increasing the pressure from the start value to the peak value then incrementally decreasing it to the end value for each cycle. For each pressure increment, subprogram PAR is called to send information to the pressure regulator then a call is made to subprogram READDATA to record the instrument readings.
- 7) Subprogram OUTFILE prompts the operator for the name of the output file and writes the heading information to the file.

- 8) Subprogram PAR sends control information to the pressure regulator via the parallel communications port.
- 9) Subprogram PAUSE holds the program in a loop until the specified time interval has elapsed.
- 10) Subprogram RANGECHECK evaluates the integer returned from a call to the data-acquisition hardware to determine if the value exceeds the predefined limits.
- 11) Subprogram READDATA reads the output signal of each instrument ten times. Each reading is checked to insure it is not out-of-range. If an out-of-range value is detected, the test is suspended until the operator gives the command to continue by pressing a key on the keyboard. For each instrument, a zero reading is subtracted from the average of the ten readings and the resulting value is converted to engineering units. The data are written to the data file and displayed on the screen.
- 12) Subprogram READZERO reads the initial output signals of the instruments. These values represent the zero force or pressure readings for each instrument and are subtracted from subsequent readings to obtain the measured force or pressure.
- 13) Subprogram SETSUPPLY guides the operator through the setting of the pressure supplied to the computer controlled pressure regulator.
- 14) Subprogram TONE produces a short tone from the speaker on the computer.
- 15) Subprogram TRANSA copies the data from drive C to drive A during the test.

16) Subprogram UPDOWN generates the specified number of load/unload cycles by increasing the pressure from the start value to the peak value then decreasing it to the end value for each cycle. For each pressure value, subprogram PAR is called to send information to the pressure regulator then a call is made to subprogram READDATA to record the instrument readings.

A.3 LISTING OF PROGRAM KOPAR.BAS

```

*****
'* PROGRAM KOPAR.BAS *
'* Program KOPAR.BAS controls the test sequence for lateral earth *
'* pressure testing using the Instrumented Oedometer and addresses the *
'* MetraByte data-acquisition hardware to monitor the test. *
*****

DECLARE SUB tone ()
DECLARE SUB transA ()
DECLARE SUB pause (dt!)
DECLARE SUB alarm ()
DECLARE SUB initdas8 ()
DECLARE SUB errorcodes (flag%)
DECLARE SUB anykey ()
DECLARE SUB rangecheck (j%, bits%, flag2%())
DECLARE SUB par (i%)
DECLARE SUB setsupply ()
DECLARE SUB updown (st%, pk%, nd%)
DECLARE SUB outfile ()
DECLARE SUB readzero ()
DECLARE SUB readdata ()
DECLARE SUB loops (n%, st%, pk%, nd%)
DIM lt%(0 TO 1)
DIM SHARED cal(1 TO 3), zero(1 TO 3), plast%, f$
DIM nslow%(20), pssb%(20), ppsb%(20), pesb%(20), nfast%(20), pssf%(20)
DIM ppsf%(20), pesf%(20), nslowe%(20), psse%(20), ppse%(20), pese%(20)

CLS
CALL par(0)

ON KEY(1) GOSUB quit
KEY(1) ON

CALL outfile

cal(1) = 66.53
cal(2) = 67.68
cal(3) = 108.65

CALL initdas8

lt%(0) = 1
lt%(1) = 3

CALL dash8(1, lt%(0), flag%)

```

```

CALL dash8(2, 1, flag%)

CALL readzero
CALL setsupply
CALL readzero
CLS
LOCATE 5, 1
PRINT "      Open Valve 2 and Close Valve 3."
PRINT
PRINT
PRINT "      PRESS ANY KEY TO CONTINUE"
anykey
CLS
i% = 0
DO
  i% = i% + 1
  CLS
  INPUT " Enter Number of Slow Cycles to Begin Test : ", nslowb%(i%)
  IF nslowb%(i%) > 0 THEN
    INPUT " Pressure Start Setting : ", pssb%(i%)
    INPUT " Pressure Peak Setting : ", ppsb%(i%)
    INPUT " Pressure End Setting : ", pesb%(i%)
  END IF
  PRINT
  INPUT " Enter Number of Fast Cycles During Test : ", nfast%(i%)
  IF nfast%(i%) > 0 THEN
    INPUT " Pressure Start Setting : ", pssf%(i%)
    INPUT " Pressure Peak Setting : ", ppsf%(i%)
    INPUT " Pressure End Setting : ", pesf%(i%)
  END IF
  PRINT
  INPUT " Enter Number of Slow Cycles to End Test : ", nslowe%(i%)
  IF nslowe%(i%) THEN
    INPUT " Pressure Start Setting : ", psse%(i%)
    INPUT " Pressure Peak Setting : ", ppse%(i%)
    INPUT " Pressure End Setting : ", pese%(i%)
  END IF
  PRINT
  PRINT " Press M to Enter More Cycles OR B to Begin the Test"
  DO
    k$ = UCASE$(INKEY$)
    LOOP UNTIL k$ = "M" OR k$ = "B"
  CLS
LOOP UNTIL k$ = "B"
plast% = 0
ncyclesets% = i%
FOR i% = 1 TO ncyclesets%

  CALL loops(nslowb%(i%), pssb%(i%), ppsb%(i%), pesb%(i%))

  FOR j% = 1 TO nfast%(i%)
    LOCATE 20, 5
    PRINT USING "Load Cycle #### of #### Fast Cycles."; j%; nfast%(i%)
    CALL updown(pssf%(i%), ppsf%(i%), pesf%(i%))
  NEXT j%

  CALL loops(nslowe%(i%), psse%(i%), ppse%(i%), pese%(i%))
  CALL transA
NEXT i%
CALL par(0)
CALL readdata
CLS

quit:
END

```

SUB alarm

```
*****  
'* SUBPROGRAM ALARM *  
*****
```

```
SOUND 100, .5  
SOUND 200, .5  
SOUND 300, .5  
SOUND 400, .5  
SOUND 500, .5  
SOUND 600, .5  
SOUND 700, .5  
SOUND 800, .5  
SOUND 900, .5  
SOUND 1000, .5  
SOUND 1100, .5  
SOUND 1200, .5  
SOUND 1300, .5  
SOUND 1400, .5  
SOUND 1500, .5  
SOUND 1600, .5  
SOUND 1700, .5  
pause .25  
FOR i = 1 TO 2  
SOUND 1200, 3  
SOUND 70, 6  
pause .1  
NEXT
```

END SUB

SUB anykey

```
*****  
'* SUBPROGRAM ANYKEY *  
*****
```

```
DO  
LOOP UNTIL INKEY$ <> ""
```

END SUB

SUB errorcodes (flag%)

```
*****  
'* SUBPROGRAM ERRORCODES *  
*****
```

```
SELECT CASE flag%  
CASE 1  
CLS  
LOCATE 20, 10  
PRINT "Failure to initialize base address using mode 0"  
END  
CASE 2  
CLS  
LOCATE 20, 10  
PRINT "Mode number out of range"  
END  
CASE 3  
CLS  
LOCATE 20, 10  
PRINT "Base address out of range"  
END  
CASE 4  
CLS  
LOCATE 20, 10  
PRINT "Scan limits out of range"
```

```

        END
    CASE 5
        CLS
        LOCATE 20, 10
        PRINT "Multiplexer channel address out of range"
        END
    CASE 6
        CLS
        LOCATE 20, 10
        PRINT "Analog to digital timeout (not good)"
        END
    CASE 7
        CLS
        LOCATE 20, 10
        PRINT "Interrupt level out of range"
        END
    CASE ELSE
END SELECT
END SUB
SUB initdas8
*****
'* SUBPROGRAM INITDAS8 *
*****

'-----
' Initialize DASH-8 with mode 0 command
'-----
        md% = 0
        basadr% = &H300           'base address
        flag% = 0                 'meaningless

'-----
' Library function call
'-----
        CALL dash8(md%, basadr%, flag%)

'-----
' Check to see that there is no error in the installation
'-----
        CALL errorcodes(flag%)

END SUB

SUB loops (n%, st%, pk%, nd%)
*****
'* SUBPROGRAM LOOPS *
*****
CLS
FOR i% = 1 TO n%
    IF (i% = 1 AND st% <> plast%) OR (i% > 1 AND nd% <> st%) THEN
        CALL par(st%)
        CALL readdata
    END IF
    FOR j% = (st% + 1) TO pk%
        CALL par(j%)
        readdata
    NEXT j%
    FOR j% = (pk% - 1) TO nd% STEP -1
        CALL par(j%)
        readdata
    NEXT j%
NEXT i%
plast% = nd%
CLS
END SUB

```

```

SUB outfile
*****
'* SUBPROGRAM OUTFILE *
*****

CLS
PRINT " ENTER NAME FOR OUTPUT FILE : ";
INPUT " ", f$
CLS
OPEN f$ FOR OUTPUT AS #2
PRINT #2, " LOAD LOAD "
PRINT #2, " CELL CELL VERT. LAT."
PRINT #2, " No.1 No.2 PRESS PRESS Ko"
PRINT #2, " (LBS) (LBS) (PSI) (PSI)"
PRINT #2,

END SUB

SUB par (i%)
*****
'* SUBPROGRAM PAR *
*****
OUT &H378, i%

END SUB

SUB pause (dt)
*****
'* SUBPROGRAM PAUSE *
*****
t0 = TIMER
DO
LOOP UNTIL (TIMER - t0) >= dt
END SUB

SUB rangecheck (j%, bits%, flag2%())
*****
'* SUBPROGRAM RANGECHECK *
*****

IF bits% >= 2047 OR bits% <= -2047 THEN
flag2%(j%) = 1
END IF

END SUB

SUB readdata
*****
'* SUBPROGRAM READDATA *
*****
DIM s(1 TO 3), flag2%(1 TO 3), reading(1 TO 3)

t0 = TIMER
DO
FOR i% = 1 TO 3
s(i%) = 0
flag2%(i%) = 0
NEXT i%
FOR i% = 1 TO 10
FOR j% = 1 TO 3
CALL dash8(4, bits%, flag%)
CALL errorcodes(flag%)
CALL rangecheck(j%, bits%, flag2%())
s(j%) = s(j%) + bits% / 10!
NEXT j%
NEXT i%
IF flag2%(1) OR flag2%(2) OR flag2%(3) THEN
CLS

```

```

LOCATE 5, 1
FOR i% = 1 TO 3
  IF flag2%(i%) THEN
    PRINT USING " Channel # is out of range."; i%
  END IF
NEXT i%
PRINT
PRINT
PRINT " PRESS ANY KEY TO CONTINUE"
CALL alarm
anykey
CLS
t0 = TIMER
ELSE
  FOR i% = 1 TO 3
    reading(i%) = (s(i%) - zero(i%)) / cal(i%)
  NEXT
  ph = (reading(1) + reading(2)) / 6!
  IF reading(3) > 0! THEN
    ko = ph / reading(3)
  END IF
  LOCATE 10, 1
  PRINT USING " H. Press. = ##.## psi"; ph
  PRINT USING " V. Press. = ##.## psi"; reading(3)
  PRINT USING " Ko = #.## "; ko

  IF TIMER - t0 > 5 THEN
    CALL tone
    PRINT #2, USING " ##.## ##.## ##.## ##.## ##.##"; reading(1); reading(2);
reading(3); ph; ko
    EXIT DO
  END IF
END IF
LOOP

END SUB

SUB readzero
*****
'* SUBPROGRAM READZERO *
*****
DIM flag2%(1 TO 3)
CLS
LOCATE 5, 1
PRINT " Prepare System for Recording Zero Readings."
PRINT
PRINT " PRESS ANY KEY TO CONTINUE"
anykey
CLS

DO
  FOR i% = 1 TO 3
    zero(i%) = 0
    flag2%(i%) = 0
  NEXT i%
  FOR i% = 1 TO 10
    FOR j% = 1 TO 3
      CALL dash8(4, bits%, flag%)
      CALL errorcodes(flag%)
      CALL rangecheck(j%, bits%, flag2%())
      zero(j%) = zero(j%) + bits% / 10!
    NEXT j%
  NEXT i%
  IF flag2%(1) OR flag2%(2) OR flag2%(3) THEN
    FOR i% = 1 TO 3
      IF flag2%(i%) THEN
        PRINT USING " Channel # was out of range during zero readings."; i%
      END IF
    NEXT i%
  END IF
END DO

```

```

        END IF
    NEXT i%
    PRINT
    PRINT "    PRESS ANY KEY TO CONTINUE"
    CALL alarm
    anykey
    CLS
ELSE
    EXIT DO
END IF
LOOP UNTIL UCASE$(INKEY$) = "Q"
CLS

END SUB

SUB setsupply
'*****
'* SUBPROGRAM SETSUPPLY *
'*****
DIM s(1 TO 3), reading(1 TO 3), flag2%(1 TO 3)

CLS
LOCATE 5, 1
PRINT "    Connect Supply Pressure and Close Valve 2."
PRINT
PRINT
PRINT "    PRESS ANY KEY TO CONTINUE"
anykey
CLS
par 15
LOCATE 15, 1
PRINT "Press C to Continue"
DO
    FOR i% = 1 TO 3
        s(i%) = 0
        flag2%(i%) = 0
    NEXT i%
    FOR i% = 1 TO 10
        FOR j% = 1 TO 3
            CALL dash8(4, bits%, flag%)
            CALL errorcodes(flag%)
            CALL rangecheck(j%, bits%, flag2%())
            s(j%) = s(j%) + bits% / 10!
        NEXT j%
    NEXT i%
    IF flag2%(1) OR flag2%(2) OR flag2%(3) THEN
        CLS
        FOR i% = 1 TO 3
            IF flag2%(i%) THEN
                PRINT USING "    Channel # is out of range."; i%
            END IF
        NEXT i%
        PRINT
        PRINT
        PRINT "    PRESS ANY KEY TO CONTINUE"
        CALL alarm
        anykey
        CLS
    END IF
ELSE
    FOR i% = 1 TO 3
        reading(i%) = (s(i%) - zero(i%)) / cal(i%)
    NEXT i%

    LOCATE 10, 1
    PRINT USING "    LOAD 1 = ##.## lbs"; reading(1)
    PRINT USING "    LOAD 2 = ##.## lbs"; reading(2)
    PRINT USING "    Pressure = ##.## psi"; reading(3)

```

```

        k$ = UCASE$(INKEY$)
        t0 = TIMER
        DO
        LOOP UNTIL (TIMER - t0) > .2
    END IF
    LOOP UNTIL k$ = "C"
    CLS
    par 0

END SUB
SUB tone
'*****
'* SUBPROGRAM TONE *
'*****
    SOUND 1500, 1
    SOUND 400, 1.5
    pause 1
END SUB

SUB transA
'*****
'* SUBPROGRAM TRANSA *
'*****
    CLS
    LOCATE 10, 1
    PRINT " TRANSFERING DATA FILE TO DRIVE A:"
    CLOSE #2
    cpy$ = "copy " + f$ + " A:"
    SHELL cpy$
    OPEN f$ FOR APPEND AS #2
    CLS
END SUB

SUB updown (st%, pk%, nd%)
'*****
'* SUBPROGRAM UPDOWN *
'*****

    IF st% <> plast% THEN
        CALL par(st%)
        CALL readdata
    END IF
    IF pk% <> st% THEN
        CALL par(pk%)
        CALL readdata
    END IF
    IF nd% <> pk% THEN
        CALL par(nd%)
        CALL readdata
    END IF
    plast% = nd%
END SUB

```

APPENDIX B
DATA-ACQUISITION COMPUTER PROGRAM AND MASTER DATA FILE
FOR THE INSTRUMENTED RETAINING WALL FACILITY

B.1 INTRODUCTION

During a test in the Instrumented Retaining Wall Facility, the instrument readings are recorded by a microcomputer-based data-acquisition system. The data-acquisition and storage functions are controlled by two programs written in Microsoft QuickBasic. The first program, EP.BAS, is executed each time a set of readings is to be recorded. If, by responding to a program prompt, the operator indicates that fill thickness measurements are to be recorded, EP.BAS initiates the second program, UDM2.BAS, to perform this task.

Both of the programs mentioned above utilize proprietary library functions provided by the manufacturers of the data-acquisition hardware. Program EP.BAS calls library functions provided by METRABYTE Corporation for use with the analog-to-digital hardware and the frequency counter. Program UDM2.BAS calls library functions provided by Conraq Technologies Corporation for use with the ultrasonic distance measuring system.

The file MASTER.ZZZ contains calibration factors, channel connection information, and location information for each of the instruments and flow control information for the data-acquisition programs.

B.2 PROGRAM EP.BAS

B.2.1 Function of Program Segments

- 1) Main program EP.BAS does the following:
 - a) Declares the subprograms,
 - b) Defines the variables types,
 - c) Dimensions the array variables and identifies variables that are shared between the program segments,
 - d) Initializes program variables, computer settings, and data-acquisition hardware,
 - e) Initiates the data-acquisition sequence for all of the instruments, except the ultrasonic distance measuring system, by calling subprogram FILEOUT,
 - f) Prompts the operator to indicate if distance measurements are to be recorded, and
 - g) Initiates program UDM2.BAS to record the distance measurements if instructed to do so.
- 2) Subprogram ANYKEY delays the program until one of the keyboard keys is pressed.
- 3) Subprogram CONNECTIONS reads connection, location and calibration information from the file MASTER.ZZZ for each the instruments.
- 4) Subprogram CTM5DIO addresses the CTM-05 hardware to send a four bit number to the relay board used to interface with the Carlson earth pressure cells.

- 5) Subprogram ERRORCODES prints an error message on the screen if an error is encountered during a library call to the data-acquisition hardware.
- 6) Subprogram FILEOUT prompts the operator to specify if the output is to be written to a new file or appended to the most recently used data file. If a new file is to be used, the operator is prompted to enter the file name and subprogram NEWOUTFILE is called. This call is followed by a call to subprogram LASTFILEOUT to update the flow control information in file MASTER.ZZZ.

If the most recently used data file is to be appended, the name of that file is read from the file MASTER.ZZZ via a call to LASTFILEOUT, the data file is opened, and the zero readings are read from the file. After instructing the operator to adjust the power supply voltage and receiving the instruction to continue, a call is made to subprogram TESTDATA to initiate the data recording sequence.

- 7) Subprogram INITCTM5 initializes the MetraByte CTM-05 data-acquisition hardware.
- 8) Subprogram INITDAS8 initializes the MetraByte DAS-8 data-acquisition hardware.
- 9) Subprogram LASTFILEOUT reads (or writes) the data file name from (or to) the file MASTER.ZZZ. If the write option is used, the zero-or-data parameter in MASTER.ZZZ is updated.
- 10) Subprogram NEWFILEOUT begins a new output file by writing header information to the file and recording the zero readings for each of the instruments.

- 11) Subprogram PAUSE holds the program in a loop until the specified time interval has elapsed.
- 12) Subprogram READCARLSON reads the Carlson earth pressure cells. Four readings are required for each of the Carlson instruments. For each of these readings, the signal is recorded forty times and an average value is used. The four readings are then converted to measurements of temperature and pressure using the calibration constants and zero readings.
- 13) Subprogram READGEONOR addresses the MetraByte CTM-05 to record the Geonor earth pressure cells. For each instrument, the average of three frequency measurements is converted to engineering units.
- 14) Subprogram READGLOETZL records each of the Gloetzl earth pressure cells by taking the average of thirty readings and converting it to engineering units.
- 15) Subprogram READHLOAD records each of the horizontal force transducers by taking the average of thirty readings and converting it to engineering units.
- 16) Subprogram READLVDT records each of the displacement transducers by taking the average of thirty readings and converting it to engineering units.
- 17) Subprogram READMUX addresses the specified channel of the analog-to-digital system and returns an integer value corresponding to the level of the signal connected to that channel.
- 18) Subprogram READTC records each of the thermocouples by taking the average of twenty readings and converting it to engineering units.

- 19) Subprogram READVLOAD records each of the vertical force transducers by taking the average of thirty readings and converting it to engineering units.
- 20) Subprogram READZEROFIL reads the zero readings for each of the instruments from the data file.
- 21) Subprogram SKIP moves the file pointer in a file to the line following the next occurrence of a period as the first non-blank character on a line.
- 22) Subprogram TESTDATA calls the various subroutines to record the instruments as data values and writes the information to the data file.

B.2.2 Listing of Program EP.BAS

```

*****
*****          PROGRAM EP.BAS          *****
*****
'* Controls the data-acquisition and recording functions during testing  *
'* with the Instrumented Retaining Wall Facility.                        *
*****

-----
'   Declare Subroutines
-----

DECLARE SUB readmux (DasChan%, ExpChan%, Bits%)
DECLARE SUB readlvd (Disp1!(), z%)
DECLARE SUB fileout ()
DECLARE SUB initdas8 ()
DECLARE SUB errorcodes (flag%, md%)
DECLARE SUB connections ()
DECLARE SUB newoutfile ()
DECLARE SUB anykey ()
DECLARE SUB readhload (hforce!(), z%)
DECLARE SUB readvload (vforce!(), z%)
DECLARE SUB readgeonor (pressure!(), z%)
DECLARE SUB readcarlson (pressure!(), z%)
DECLARE SUB initctm5 ()
DECLARE SUB ctm5dio (io%)
DECLARE SUB pause (interval!)
DECLARE SUB skip (filenum%)
DECLARE SUB readgloetzl (pres!(), z%)
DECLARE SUB lastfileout (Foutlast$, ZorD$, Opt$)
DECLARE SUB readzerofile ()
DECLARE SUB testdata ()
DECLARE SUB readtc (tempF!())

```

' Define Types

```
TYPE gtz
  Label AS STRING * 10
  y AS SINGLE
  z AS SINGLE
  DasChan AS INTEGER
  ExpChan AS INTEGER
  Calib AS SINGLE
  zero AS SINGLE
END TYPE
```

```
TYPE cr1
  Label AS STRING * 9
  y AS SINGLE
  z AS SINGLE
  DasChan AS INTEGER
  ExpChan1 AS INTEGER
  ExpChan4 AS INTEGER
  Ctmio AS INTEGER
  Res0 AS SINGLE
  DegPerOhm AS SINGLE
  Cnst AS SINGLE
  Rat0 AS SINGLE
  DRat AS SINGLE
  Calib AS SINGLE
  zero AS SINGLE
  Temp AS SINGLE
END TYPE
```

```
TYPE gnr
  Label AS STRING * 8
  y AS SINGLE
  z AS SINGLE
  CtmChan AS INTEGER
  Calib AS SINGLE
  zero AS SINGLE
END TYPE
```

```
TYPE load
  Label AS STRING * 9
  DasChan AS INTEGER
  ExpChan AS INTEGER
  Calib AS SINGLE
  zero AS SINGLE
END TYPE
```

```
TYPE Disp
  Label AS STRING * 6
  y AS SINGLE
  z AS SINGLE
  DasChan AS INTEGER
  ExpChan AS INTEGER
  zero AS SINGLE
END TYPE
```

' Dimension Variables

```
DIM SHARED Gloetzl(1 TO 11) AS gtz
DIM SHARED Carlson(1 TO 4) AS cr1
DIM SHARED Geonor(1 TO 2) AS gnr
DIM SHARED Hload(1 TO 12) AS load
DIM SHARED Vload(1 TO 8) AS load
```

```
DIM SHARED Lvdt(1 TO 9) AS Disp
DIM SHARED Dio%(0 TO 9), lt%(0 TO 1)
DIM SHARED LVDTcal(1 TO 9, 0 TO 10), TempZero(6)
COMMON SHARED path$, er%, er$, UdmRef, LocLastFileName%
```

```
'-----
' Start error trapping
'-----
```

```
ON ERROR GOTO handler
```

```
'-----
' Set Screen Mode
'-----
```

```
SCREEN 2
```

```
'-----
' Set F1 key to exit program
'-----
```

```
ON KEY(1) GOSUB quit
KEY(1) ON
```

```
'-----
' Initialize the DAS-8 and the CTM-05
'-----
```

```
CALL initctm5
CALL initdas8
```

```
'-----
' Read the transducer connection/location/calibration file.
'-----
```

```
CALL connections
```

```
'-----
' Select output file name and proceed with data acquisition.
'-----
```

```
CALL fileout
```

```
'-----
' Ask Operator if Distance Measurements are to be taken.
'-----
```

```
LOCATE 10, 1
PRINT " Measure Fill Thickness (Y or N)";
```

```
DO
  yn$ = UCASE$(INKEY$)
LOOP UNTIL yn$ = "Y" OR yn$ = "N"
CLS
```

```
'-----
' Run the Distance Measurement Program UDM2.EXE if requested to.
'-----
```

```
IF yn$ = "Y" THEN
  RUN "UDM2"
END IF
CLS
```

```
quit:
```

```
END
```

```

-----
' Error handling routine.
-----

```

handler:

```

er% = ERR
SELECT CASE ERR
CASE 76
DO
CLS
LOCATE 10, 5
PRINT "PATH "; path$; " DOES NOT EXIST - - CREATE IT? <Y/N> : ";
DO
r$ = UCASE$(INKEY$)
LOOP WHILE r$ = ""
LOOP UNTIL r$ = "Y" OR r$ = "N"
IF r$ = "Y" THEN
dr$ = LEFT$(path$, (LEN(path$) - 1))
MKDIR dr$
er% = 0
RESUME
ELSE
er$ = "ERROR - - PATH NOT FOUND"
RESUME NEXT
END IF
CASE 64
er$ = "ERROR - - BAD FILE NAME"
RESUME NEXT
CASE 68
er$ = "ERROR - - DEVICE UNAVAILABLE"
RESUME NEXT
CASE ELSE
ON ERROR GOTO 0
END SELECT
RESUME NEXT

```

SUB anykey

```

*****
'***** SUBPROGRAM anykey *****
'*****
'* Waits until the user presses a key on the keyboard. *
'*****

```

```

DO
LOOP WHILE INKEY$ = ""
CLS

```

END SUB

SUB connections

```

*****
'***** SUBPROGRAM connections *****
'*****
' Opens the file MASTER.ZZZ and reads the transducer connection, *
' location, and calibration information. *
'*****

```

```

-----
' Open MASTER.ZZZ for input
-----
OPEN "MASTER.ZZZ" FOR INPUT AS #1
-----

```

```

Read the information for Gloetzl earth pressure cells
Gloetzl(i).Label = Label for Gloetzl cell i
Gloetzl(i).y = Y coordinate of Gloetzl cell i
Gloetzl(i).z = Z coordinate of Gloetzl cell i
Gloetzl(i).DasChan = DAS-8 channel number for Gloetzl cell i
Gloetzl(i).ExpChan = EXP-16 channel number for Gloetzl cell i
Gloetzl(i).Calib = Calibration factor (psi/volt) for Gloetzl cell i

```

```

skip 1
FOR i = 1 TO 11
  INPUT #1, Gloetzl(i).Label, Gloetzl(i).y, Gloetzl(i).z
  INPUT #1, Gloetzl(i).DasChan, Gloetzl(i).ExpChan, Gloetzl(i).Calib
NEXT i

```

```

Read the information for Carlson earth pressure cells
Carlson(i).Label = Label for Carlson cell i
Carlson(i).y = Y coordinate of Carlson cell i
Carlson(i).z = Z coordinate of Carlson cell i
Carlson(i).DasChan = DAS-8 channel number for Carlson cell i
Carlson(i).ExpChan1 = First EXP-16 channel number for Carlson cell i
Carlson(i).ExpChan4 = Fourth EXP-16 channel number for Carlson cell i
Carlson(i).Ctmio = First CTM-05 value for Carlson cell i
Carlson(i).Res0 = Resistance at Zero Deg. F for Carlson cell i
Carlson(i).DegPerOhm = Degrees F per Ohm for Carlson cell i
Carlson(i).Cnst = Calibration constant (psi per 0.01 change in
resistance ratio percent) for Carlson cell i
Carlson(i).Rat0 = Resistance ratio percent at 0.0 stress and
0.0 Deg. F for Carlson cell i
Carlson(i).DRat = Change in resistance ratio percent per Deg. F
for Carlson cell i
Carlson(i).Calib = Correction factor for Carlson cell i

```

```

skip 1
FOR i = 1 TO 4
  INPUT #1, Carlson(i).Label, Carlson(i).y, Carlson(i).z
  INPUT #1, Carlson(i).DasChan, Carlson(i).ExpChan1, Carlson(i).ExpChan4
  INPUT #1, Carlson(i).Ctmio, Carlson(i).Res0, Carlson(i).DegPerOhm
  INPUT #1, Carlson(i).Cnst, Carlson(i).Rat0, Carlson(i).DRat
  INPUT #1, Carlson(i).Calib
NEXT i

```

```

Read the information for Geonor earth pressure cells
Geonor(i).Label = Label for Geonor cell i
Geonor(i).y = Y coordinate of Geonor cell i
Geonor(i).z = Z coordinate of Geonor cell i
Geonor(i).CtmChan = CTM-05 channel number for Geonor cell i
Geonor(i).Calib = Calibration factor for Geonor cell i

```

```

skip 1
FOR i = 1 TO 2
  INPUT #1, Geonor(i).Label, Geonor(i).y, Geonor(i).z, Geonor(i).CtmChan
  INPUT #1, Geonor(i).Calib
NEXT i

```

```

Read the information for horizontal load cells
Hload(i).Label = Label for load cell i
Hload(i).DasChan = DAS-8 channel number for load cell i
Hload(i).ExpChan = EXP-16 channel number for load cell i
Hload(i).Calib = Calibration factor for load cell i (lbs/bit)

```

```

skip 1

```

```

FOR i = 1 TO 12
  INPUT #1, Hload(i).Label, Hload(i).DasChan, Hload(i).ExpChan
  INPUT #1, Hload(i).Calib
NEXT i

```

```

-----
' Read the information for vertical load cells
' Vload(i).Label = Label for load cell i
' Vload(i).DasChan = DAS-8 channel number for load cell i
' Vload(i).ExpChan = EXP-16 channel number for load cell i
' Vload(i).Calib = Calibration factor for load cell i (lbs/bit)
-----

```

```

skip 1
FOR i = 1 TO 8
  INPUT #1, Vload(i).Label, Vload(i).DasChan, Vload(i).ExpChan
  INPUT #1, Vload(i).Calib
NEXT i

```

```

-----
' Skip to the information for the LVDTs
-----

```

```

skip 1

```

```

-----
' Read the information for the Displacement Transducers.
' Lvdt(i).Label = Label for Lvdt i
' Lvdt(i).y = Y coordinate of Lvdt i
' Lvdt(i).z = Z coordinate of Lvdt i
' Lvdt(i).DasChan = DAS-8 channel number for Lvdt i
' Lvdt(i).ExpChan = EXP-16 channel number for Lvdt i
-----

```

```

skip 1
FOR i = 1 TO 9
  INPUT #1, Lvdt(i).Label, Lvdt(i).y, Lvdt(i).z
  INPUT #1, Lvdt(i).DasChan, Lvdt(i).ExpChan
NEXT i

```

```

-----
' Read Calibration Information for the Displacement Transducers.
' LVDTcal(i,j) = Calibration Value (reading in bits)
' i = LVDT Number
' j = LVDT tip location
' ( j = 0, +0.500 in., in )
' ( j = 5, 0.000 in., middle )
' ( j = 10, -0.500 in., out )
-----

```

```

skip 1
FOR i% = 1 TO 8
  FOR j% = 0 TO 10
    INPUT #1, LVDTcal(i%, j%)
  NEXT j%
NEXT i%
skip 1
FOR j% = 0 TO 10
  INPUT #1, LVDTcal(9, j%)
NEXT j%
skip 1
LocLastFileName% = SEEK(1)

```

```

-----
' Close the Input File.
-----

```

```

CLOSE 1

```

END SUB

SUB ctm5dio (io%)

```
*****  
*****          SUBPROGRAM ctm5dio          *****  
*****  
*   Outputs a number to the CTM-05 digital output ports.   *  
*****
```

```
-----  
*   Use MODE 6 of the MetraByte CTM-05 to control the output on OPO - OP3.  
-----
```

```
md% = 6  
Dio%(0) = io%  
flag% = 0  
CALL ctm5(md%, Dio%(0), flag%)
```

```
-----  
*   Check condition of error flag upon return and take action if needed.  
-----
```

```
IF flag% <> 0 THEN  
  CLS  
  LOCATE 10, 5  
  PRINT "ERROR FLAG"; flag%; "UPON RETURN FROM MODE 6 CALL TO CTM5."  
  STOP  
END IF
```

END SUB

SUB errorcodes (flag%, md%)

```
*****  
*****          SUBPROGRAM errorcodes          *****  
*****  
*   Prints a message and the flag number if an error is generated during *  
*   a call to DASH8 then stops the program.                               *  
*****
```

```
IF flag% <> 0 THEN  
  CLS  
  LOCATE 10, 5  
  PRINT "ERROR FLAG"; flag%; "UPON RETURN FROM MODE";  
  PRINT md%; "CALL TO DAS8."  
END IF  
SELECT CASE flag%  
  CASE 1  
    LOCATE 12, 5  
    PRINT "Failure to initialize base address using mode 0"  
    STOP  
  CASE 2  
    LOCATE 12, 5  
    PRINT "Mode number out of range"  
    STOP  
  CASE 3  
    LOCATE 12, 5  
    PRINT "Base address out of range"  
    STOP  
  CASE 4  
    LOCATE 12, 5  
    PRINT "Scan limits out of range"  
    STOP  
  CASE 5  
    LOCATE 12, 5  
    PRINT "Multiplexer channel address out of range"  
    STOP
```

```

CASE 6
  LOCATE 12, 5
  PRINT "Analog to digital timeout (not good)"
  STOP
CASE 7
  LOCATE 12, 5
  PRINT "Interrupt level out of range"
  STOP
CASE ELSE
END SELECT

```

END SUB

SUB fileout

```

*****
*****          SUBPROGRAM FILEOUT          *****
*****
'*  Ask for output file name and check to insure it is not already used  *
'*  in the specified path.                                               *
*****

```

```

DO
  LOCATE 10, 1
  PRINT "      OUTPUT FILE OPTIONS  - -  Select by Number"
  PRINT
  PRINT "      1.)  Begin a New Data File"
  PRINT
  PRINT "      2.)  Append The Last Data File"
  DO
    K$ = INKEY$
    Choice% = VAL(K$)
  LOOP WHILE K$ = ""
  LOOP UNTIL Choice% = 1 OR Choice% = 2

```

```

CLS
LOCATE 10, 10
PRINT "PLEASE WAIT"

```

Request output drive selection

IF Choice% = 1 THEN

```

fout$ = "C:\EPDAT\TEMP.EPD"
path$ = ""
DO
  CLS
  er% = 0
  LOCATE 12, 5
  PRINT "File extension .EPD will be added to filename."
  LOCATE 13, 5
  PRINT "      "; er$
  er$ = ""
  LOCATE 10, 5
  PRINT "Enter Drive, Subdirectory, and Filename <"; fout$; "> : ";
  INPUT "", out$
  IF out$ = "" THEN
    out$ = fout$
  END IF
  out$ = UCASE$(out$)
  IF (MID$(out$, 2, 1)) = ":" THEN
    pointer% = 1
    DO
      search% = INSTR(pointer%, out$, "\")
      IF search% > 0 THEN
        pointer% = search% + 1
      END IF
    DO

```

```

        LOOP UNTIL search% = 0
        IF search% = 0 AND pointer% = 1 THEN
            pointer% = 3
        END IF
        nchar% = LEN(out$) - pointer% + 1
        name$ = RIGHT$(out$, nchar%)
        path$ = LEFT$(out$, (LEN(out$) - nchar%))
    ELSE
        name$ = out$
        path$ = ""
    END IF
    search% = INSTR(name$, ".")
    IF search% > 0 THEN
        name$ = LEFT$(name$, (search% - 1))
    END IF
    IF LEN(name$) > 8 THEN
        name$ = LEFT$(name$, 8)
    END IF
    fout$ = path$ + name$ + ".EPD"
    CLOSE #2
    OPEN fout$ FOR APPEND AS #2
    IF er% = 0 THEN
        length = LOF(2)

```

 If user specified file exists, ask if it should be overwritten

```

        IF length > 0 THEN
            CLS
            LOCATE 10, 5
            PRINT fout$; " ALREADY EXISTS - - OVERWRITE IT? <Y/N> : ";
            DO
                r$ = UCASE$(INKEY$)
                LOOP UNTIL r$ = "Y" OR r$ = "N"

```

 If user specified file is not to be overwritten, ask for new file name

```

        END IF
    END IF
    LOOP UNTIL (r$ = "Y" OR length = 0) AND (er% = 0)
    CLOSE #2

```

 Open selected file for output and clear screen then call newoutfile

```

    OPEN fout$ FOR OUTPUT AS #2
    CLS
    CALL newoutfile
    CLOSE #2
    CALL lastfileout(fout$, "ZERO", "W")
ELSE
    CALL lastfileout(fout$, "Not Used During R Option", "R")
    CALL lastfileout(fout$, "DATA", "W")
    OPEN fout$ FOR INPUT AS #2
    CALL readzerofile
    CLOSE #2
    CLS
    LOCATE 10, 1
    PRINT "      Check Setting of Power Supply (10.404 VDC)"
    PRINT
    PRINT "      When Ready to Record Data - - Press Any Key"
    anykey
    OPEN fout$ FOR APPEND AS #2
    CALL testdata

```

```

        CLOSE #2
    END IF

END SUB

SUB initctm5
'*****
'*****          SUBPROGRAM initctm5          *****
'*****
'* Initialize the CTM-05          *
'*****

    Dio%(0) = &H310   'I/O address at Hex 310
    Dio%(1) = 10     'Fout divider of 10
    Dio%(2) = 15     'Fout source = F5 (100Hz) for Fout = 10Hz
    Dio%(3) = 0      'Compare 2 disable
    Dio%(4) = 0      'Compare 1 disable
    Dio%(5) = 0      'Time of day disabled
    flag% = 0
    md% = 0
    CALL ctm5(md%, Dio%(0), flag%)

'-----
' Check condition of error flag upon return and take action if needed.
'-----

    IF flag% <> 0 THEN
        CLS
        LOCATE 10, 5
        PRINT "ERROR FLAG "; flag%; " UPON RETURN FROM MODE 0 CALL TO CTM5."
        STOP
    END IF

END SUB

SUB initdas8
'*****
'*****          SUBPROGRAM initdas8          *****
'*****
'* Initialize the DAS-8          *
'*****

    md% = 0
    basadr% = &H330   'base address
    flag% = 0        'meaningless

'-----
' Library function call
'-----

    CALL dash8(md%, basadr%, flag%)

'-----
' Check to see that there is no error in the installation
'-----

    CALL errorcodes(flag%, md%)

END SUB

SUB lastfileout (Foutlast$, ZorD$, Opt$)
'*****
'*****          SUBPROGRAM lastfileout          *****
'*****
'* Reads or Writes the data file name to the file MASTER.ZZZ and writes *
'*****

```

```
'* the identifier ZorD$ if Opt$ = W. *
*****
```

```
IF UCASE$(Opt$) = "R" THEN
  OPEN "MASTER.ZZZ" FOR INPUT AS #1
  SEEK 1, LocLastFileName%
  LINE INPUT #1, Foutlast$
  CLOSE #1
ELSEIF UCASE$(Opt$) = "W" THEN
  OPEN "MASTER.ZZZ" FOR APPEND AS #1
  SEEK 1, LocLastFileName%
  PRINT #1, Foutlast$
  PRINT #1, ZorD$
  CLOSE #1
END IF
```

```
END SUB
```

```
SUB newoutfile
```

```
*****
***** SUBPROGRAM newoutfile *****
*****
'* Create a new output file and write test information to that file *
```

```
DIM hforce(12), vforce(8), pres(11), distance(14), Displ(9), tempF(10)
```

```
-----
Write header information to file.
```

```
PRINT #2, "Geotechnical Engineering Division, Earth Pressures";
PRINT #2, " Research Program"
PRINT #2, "Charles Edward Via, Jr. Department of Civil Engineering"
PRINT #2, "Virginia Polytechnic Institute and State University"
PRINT #2, "Blacksburg, Virginia 24061-0105"
PRINT #2,
PRINT #2,
```

```
-----
Ask for test title and write title to file.
```

```
CLS
LOCATE 10, 5
INPUT "Enter Title for this Test : ", title$
PRINT #2, "Title..... : "; title$
```

```
-----
Ask for test date, reset computer date if needed, write date to file.
```

```
d$ = DATE$
CLS
LOCATE 10, 5
PRINT "Enter Test Date < "; d$; " > : ";
INPUT "", d$
IF d$ = "" THEN
  d$ = DATE$
ELSE
  DATE$ = d$
END IF
PRINT #2, "Date..... : "; d$
```

```
-----
Write soil type to file.
```



```
PRINT #2, "-----"
PRINT #2,
      &&&&&&&&&      ##.##      ##.##      #.###
PRINT #2, "Carlson    Zero      Temp.     Calib."
PRINT #2, "Inst. ID    Reading   Reading   Factor"
PRINT #2, "                (psi)      (Deg. F.) (Carlson/True)"
PRINT #2, "."

FOR i% = 1 TO 4
  PRINT #2, USING "&      ##.##      ##.##      #.###"; Carlson(i%).Label;
Carlson(i%).zero; Carlson(i%).Temp; Carlson(i%).Calib
NEXT i%
PRINT #2,
PRINT #2,
```

Take zero readings for Geonor cells and write them to file.

```
CALL readgeonor(pres(), 0)
PRINT #2, "-----"
PRINT #2,
      &&&&&&&&&      #####      ####.#
PRINT #2, "Geonor      Zero      Calib."
PRINT #2, "Inst. ID    Reading   Factor"
PRINT #2, "                (Hz)      (Hz/psi)"
PRINT #2, "."

FOR i% = 1 TO 1
  PRINT #2, USING "&      #####      ####.#"; Geonor(i%).Label; Geonor(i%).zero;
Geonor(i%).Calib
NEXT i%
PRINT #2,
PRINT #2,
```

Take zero readings for horizontal load cells and write them to file.

```
CALL readhload(hforce(), 0)
PRINT #2, "-----"
PRINT #2,
      &&&&&&&&&      #####.##      #.###
PRINT #2, "H Load      Zero      Calib."
PRINT #2, "Inst. ID    Reading   Factor"
PRINT #2, "                (Bits)   (Lbs/Bit)"
PRINT #2, "."

FOR i% = 1 TO 12
  PRINT #2, USING "&      #####.##      #.###"; Hload(i%).Label; Hload(i%).zero;
Hload(i%).Calib
NEXT i%
PRINT #2,
PRINT #2,
```

Take zero readings for vertical load cells and write them to file.

```
CALL readvload(vforce(), 0)

PRINT #2, "-----"
PRINT #2,
      &&&&&&&&&      #####.##      #.###
PRINT #2, "V Load      Zero      Calib."
PRINT #2, "Inst. ID    Reading   Factor"
PRINT #2, "                (Bits)   (Lbs/Bit)"
PRINT #2, "
```

```

PRINT #2, "."
FOR i% = 1 TO 8
  PRINT #2, USING "&      ####.##      #.###"; Vload(i%).Label; Vload(i%).zero;
Vload(i%).Calib
NEXT i%
PRINT #2,
PRINT #2,

```

```

Take zero readings for LVDTs and write them to file.

```

```

CALL readlvdt(Displ(), 0)

PRINT #2, "-----"
PRINT #2,
      &&&&&&      ##.####
PRINT #2, "LVDT      Zero"
PRINT #2, "Inst. ID    Reading"
PRINT #2, "      (inches)"
PRINT #2, "."

FOR i% = 1 TO 9
  PRINT #2, USING "&      ##.####"; Lvdt(i%).Label; Lvdt(i%).zero
NEXT i%
PRINT #2,
PRINT #2,

```

```

Take zero readings for Temperature and write them to file.

```

```

CALL readtc(tempF())

PRINT #2, "-----"
PRINT #2,
      Tcouple #      ###.#
PRINT #2, "Tcouple      Zero"
PRINT #2, "Inst. ID    Reading"
PRINT #2, "      (Deg. F)"
PRINT #2, "."

FOR i% = 1 TO 6
  PRINT #2, USING "Tcouple #      ###.#"; i%; tempF(i%)
NEXT i%
PRINT #2,
PRINT #2,

```

END SUB

SUB pause (interval)

```

*****
*****          SUBPROGRAM pause          *****
*****
* Program will remain in this subroutine for INTERVAL seconds then *
* return to the calling routine *
*****

```

```

T0 = TIMER
DO
  Dt = TIMER - T0
  LOOP WHILE Dt < interval

```

END SUB

SUB readcarlson (pressure(), z%)

```

*****
*****          SUBPROGRAM readcarlson          *****
*****
*   Read the Carlson earth pressure cells.   *
*****

-----
'   Dimension Variables
-----

DIM Rdg1(1 TO 4), Rdg2(1 TO 4), Rdg3(1 TO 4), Rdg4(1 TO 4)

-----
'   Clear Screen and Print Message to Operator
-----

CLS
LOCATE 10, 5
PRINT "Reading Carlson Earth Pressure Cells - - PLEASE WAIT."

-----
'   Set values for precision resistors and reference voltages
-----

Rp1 = 80!
Rp2 = 39.97
Vs = 1.994
Va = .996

-----
'   Loop four times to read the four Carlson E. P. cells
-----

FOR i% = 1 TO 4

-----
'   Set variable for the DASH-8 channel number for the first three cases
-----

ChD8% = Carlson(i%).DasChan

-----
'   Read Carlson instrument i, case 1 connection arrangement.
-----

Sum& = 0
sw% = Carlson(i%).Ctmio + 2
Ch% = Carlson(i%).ExpChan1
CALL ctm5dio(sw%)
pause .5

FOR j% = 1 TO 40
    CALL readmux(ChD8%, Ch%, Bits%)
    Sum& = Sum& + Bits%
NEXT j%

bitss = Sum& / 40!
V1 = (bitss / 2048) * .1
Rdg1(i%) = (Va + V1) / (Vs - Va - V1)

'Gain is 50
'(R1+Rc)/(R2+Rc)

-----
'   Read Carlson instrument i, case 2 connection arrangement.
-----

Sum& = 0
sw% = Carlson(i%).Ctmio + 1
Ch% = Carlson(i%).ExpChan1 + 1

```

```

CALL ctm5dio(sw%)
pause .5

FOR j% = 1 TO 40
  CALL readmux(ChD8%, Ch%, Bits%)
  Sum& = Sum& + Bits%
NEXT j%

bitss = Sum& / 40!
V2 = (bitss / 2048) * .1
Rdg2(i%) = ((Vs - Va - V2) / (Va + V2)) * Rp1

```

```

'Gain is 50
'R1+R2+2*Rc

```

```

-----
Read Carlson instrument i, case 3 connection arrangement.
-----

```

```

Sum& = 0
Ch% = Carlson(i%).ExpChan1 + 2

FOR j% = 1 TO 40
  CALL readmux(ChD8%, Ch%, Bits%)
  Sum& = Sum& + Bits%
NEXT j%

```

```

bitss = Sum& / 40!
V3 = (bitss / 2048) * .1
Rdg3(i%) = ((.4983 - V3) / (Va + V2)) * Rp1

```

```

'Gain is 50
'R2+Rc

```

```

-----
Read Carlson instrument i, case 4 connection arrangement.
-----

```

```

Sum& = 0
sw% = Carlson(i%).Ctmio
Ch% = Carlson(i%).ExpChan4
Ch8% = Carlson(i%).DasChan - 1
CALL ctm5dio(sw%)
pause .5

FOR j% = 1 TO 40
  CALL readmux(Ch8%, Ch%, Bits%)
  Sum& = Sum& + Bits%
NEXT j%

```

```

bitss = Sum& / 40!
V4 = (bitss / 2048) * .1
Rdg4(i%) = (Vs - Va - V4) / (Va + V4) * Rp2

```

```

'Gain is 50
'R2+2*Rc

```

```

NEXT i%

```

```

-----
Send 15 to the Carlson switch board to disconnect the 2 VDC supply.
-----

```

```

CALL ctm5dio(15)

```

```

-----
Calculate earth pressures based on factory calibrations.
-----

```

```

FOR i% = 1 TO 4
  Rsum = Rdg2(i%) + 2! * Rdg3(i%) - 2! * Rdg4(i%)
  RatioC2 = (Rdg4(i%) - Rdg3(i%)) / (2! * Rdg3(i%) - Rdg4(i%))
  Ratio = (RatioC2 * (Rdg1(i%) - 1!) + Rdg1(i%)) * 100
  Carlson(i%).Temp = (Rsum - Carlson(i%).Res0) * Carlson(i%).DegPerOhm
  RatZero = Carlson(i%).Rat0 + Carlson(i%).DRat * Carlson(i%).Temp
  pressure(i%) = (RatZero - Ratio) * Carlson(i%).Cnst * 100!
NEXT i%

```

```

-----
' If this call is not for zero readings, subtract the zero readings
' and factor the earth pressures in accordance with the calibration
' test results
-----

```

```

IF z% <> 0 THEN
  FOR i% = 1 TO 4
    pressure(i%) = (pressure(i%) - Carlson(i%).zero) / Carlson(i%).Calib
  NEXT i%

```

```

-----
' If this call is for zero readings, record the readings
-----

```

```

ELSE
  FOR i% = 1 TO 4
    Carlson(i%).zero = pressure(i%)
  NEXT i%
END IF

CLS

```

```

END SUB

```

```

SUB readgeonor (pressure(), z%)

```

```

*****
*****          SUBPROGRAM readgeonor          *****
*****
'*   Read the Geonor earth pressure cells.   *
*****

```

```

  DIM Count(2)

```

```

-----
' Use MODE 10 of the MetraByte CTM-05 to measure the output frequency
' of the two Geonor earth pressure cells.
-----

```

```

CLS
LOCATE 10, 5
PRINT "Reading Geonor Earth Pressure Cells - - PLEASE WAIT."

```

```

Count(1) = 0!
Count(2) = 0!

```

```

md% = 10
Dio%(0) = 1000

```

```

FOR i% = 1 TO 3
  Dio%(1) = 1
  CALL ctm5(md%, Dio%(0), flag%)
  Count(1) = Count(1) + Dio%(2) / 3!
  Dio%(1) = 2
  call ctm5(md%, Dio%(0), flag%)
  Count(2) = Count(2) + Dio%(2) / 3!
NEXT i%

```

```

-----
' If this call is not for zero readings, subtract the zero readings
' and calculate the pressures.
-----

```

```

IF z% <> 0 THEN
  FOR i% = 1 TO 1
    pressure(i%) = (Count(i%) - Geonor(i%).zero) / Geonor(i%).Calib
  
```

```

NEXT i%

-----
' If this call is for zero readings, record the readings.
-----

ELSE
  FOR i% = 1 TO 1
    Geonor(i%).zero = Count(i%)
  NEXT i%
END IF
CLS

END SUB

SUB readgloetz1 (pres(), z%)

'*****
'*****      SUBPROGRAM readgloetz1      *****
'*****
'* Sets summing variable to zero, calls READMUX 30 times for each      *
'* Gloetz1 pressure cell, calculates the average reading, in bits,      *
'* for each cell.                                                         *
'*****

CLS
LOCATE 10,5
PRINT "Reading Gloetz1 Earth Pressure Cells - - PLEASE WAIT."

-----
' Dimension Variables
-----

DIM AvgBits(11)

-----
' Call READMUX to read each channel 30 times then calculate the average.
-----

FOR i% = 1 TO 11
  Sum& = 0!
  FOR j% = 1 TO 30
    CALL readmux(Gloetz1(i%).DasChan, Gloetz1(i%).ExpChan, Bits%)
    Sum& = Sum& + Bits%
  NEXT
  AvgBits(i%) = Sum& / 30
NEXT

-----
' If this call is not for zero readings, subtract the zero readings
' and calculate the pressures.
-----

IF z% <> 0 THEN
  FOR i% = 1 TO 11
    pres(i%) = (AvgBits(i%) - Gloetz1(i%).zero) / Gloetz1(i%).Calib
  NEXT i%

-----
' If this call is for zero readings, record the readings
-----

ELSE
  FOR i% = 1 TO 11
    Gloetz1(i%).zero = AvgBits(i%)
  NEXT i%
END IF

```

```

CLS
END SUB
SUB readhload (hforce(), z%)
'*****
'*****          SUBPROGRAM readhload          *****
'*****
'*  Calls READMUX 30 times for each of the horizontal load cells,      *
'*  calculates the average reading for each channel                      *
'*****

'-----
' Dimension Variables
'-----

DIM AvgBits(12)

'-----
' Print Message for the Operator
'-----

CLS
LOCATE 10, 5
PRINT "Reading Horizontal Force Transducers - - PLEASE WAIT."

'-----
' Call READMUX to read each channel 30 times then calculate the average.
'-----

FOR i% = 1 TO 12
  Sum& = 0!
  FOR j% = 1 TO 30
    CALL readmux(Hload(i%).DasChan, Hload(i%).ExpChan, Bits%)
    Sum& = Sum& + Bits%
  NEXT
  AvgBits(i%) = Sum& / 30!
NEXT

'-----
' If this call is not for zero readings, subtract the zero readings
' and calculate the forces.
'-----

IF z% <> 0 THEN
  FOR i% = 1 TO 12
    hforce(i%) = (AvgBits(i%) - Hload(i%).zero) * Hload(i%).Calib
  NEXT i%

'-----
' If this call is for zero readings, record the readings
'-----

ELSE
  FOR i% = 1 TO 12
    Hload(i%).zero = AvgBits(i%)
  NEXT i%
END IF
CLS
END SUB
SUB readlvdv (Displ(), z%)
'*****
'*****          SUBPROGRAM readlvdv          *****
'*****

```

```
'* Sets summing variables to zero, calls READMUX 30 times for each of
'* the LVDTs, calculates the average reading for each channel
'*****
```

```
-----
' Dimension Variables
'-----
```

```
DIM AvgBits(9), position(9), outrange%(9)
```

```
CLS
LOCATE 10, 5
PRINT "Reading Displacement Transducers - - PLEASE WAIT."
```

```
-----
' Call READMUX to read each channel 30 times then calculate the average
'-----
```

```
FOR i% = 1 TO 9
  Sum& = 0
  FOR j% = 1 TO 30
    CALL readmux(Lvdt(i%).DasChan, Lvdt(i%).ExpChan, Bits%)
    Sum& = Sum& + Bits%
  NEXT
  AvgBits(i%) = Sum& / 30!
NEXT
```

```
-----
' Evaluate the LVDT output
'-----
```

```
FOR i% = 1 TO 9
```

```
-----
' Check if the LVDT is within the calibrated range. If it is not, inform
' the Operator that 9.9999 will be printed to the data file.
'-----
```

```
IF AvgBits(i%) > LVDTcal(i%, 0) AND AvgBits(i%) < LVDTcal(i%, 10) THEN
  outrange%(i%) = 1
  CLS
  LOCATE 10, 5
  PRINT USING "LVDT # is out of its Calibrated Range"; i%
  LOCATE 12, 5
  PRINT "9.9999 will be written to the data file"
  LOCATE 16, 5
  PRINT "Press Any Key to Continue"
  anykey
```

```
ELSE
```

```
-----
' Determine the LVDT tip positions
'-----
```

```
FOR j% = 1 TO 10
```

```
IF AvgBits(i%) <= LVDTcal(i%, (j% - 1)) AND AvgBits(i%) >= LVDTcal(i%, j%) THEN
  IF i% < 9 THEN
    position(i%) = ((AvgBits(i%) - LVDTcal(i%, j%)) / (LVDTcal(i%, (j% - 1)) -
LVDTcal(i%, j%))) * .1 + .1 * (5 - j%)
  ELSE
    position(i%) = ((AvgBits(i%) - LVDTcal(i%, j%)) / (LVDTcal(i%, (j% - 1)) -
LVDTcal(i%, j%))) * .02 + .02 * (5 - j%)
  END IF
  EXIT FOR
END IF
```

```

NEXT j%

END IF

NEXT i%

'-----
' If this call is not for zero readings, subtract the zero readings
'-----

IF z% <> 0 THEN
  FOR i% = 1 TO 9
    Displ(i%) = position(i%) - Lvdt(i%).zero
    IF outrange%(i%) OR Lvdt(i%).zero = 9.9999 THEN
      Displ(i%) = 9.9999
    END IF
  NEXT i%

'-----
' If this call is for zero readings, record the readings
'-----

ELSE
  FOR i% = 1 TO 9
    Lvdt(i%).zero = position(i%)
    IF outrange%(i%) THEN
      Lvdt(i%).zero = 9.9999
    END IF
  NEXT i%
END IF
CLS

END SUB

SUB readmux (DasChan%, ExpChan%, Bits%)

'*****
'*****          SUBPROGRAM readmux          *****
'*****
'*          Make analog to digital conversion for dash-8 assuming          *
'*          EXP-16 submultiplexer is used. The answer is returned          *
'*          in bits for full scale conversion ( f(gain) ).                  *
'*          Mode 1 sets the dash-8 channel number (jumper setting on        *
'*          the EXP-16                                                       *
'*****

md% = 1
flag% = 0
lt%(0) = DasChan%
lt%(1) = DasChan%
CALL dash8(md%, lt%(0), flag%)
CALL errorcodes(flag%, md%)

'-----
' Address exp-16 channel using the digital outputs, mode 14
'-----

md% = 14
op% = ExpChan%
CALL dash8(md%, op%, flag%)
CALL errorcodes(flag%, md%)

'-----
' Perform the A to D conversion using mode 4
'-----

md% = 4
CALL dash8(md%, Bits%, flag%)

```

```

IF flag% <> 0 THEN
  CALL errorcodes(flag%, md%)
END IF

END SUB

SUB readtc (tempF())

'*****
'*****          SUBPROGRAM readtc          *****
'*****
'* Reads the 6 thermocouples.                *
'*****

'-----
' Dimension Variables.
'-----

DIM tc(10), tempC(10)

'-----
' Print Message for User.
'-----

CLS
LOCATE 10, 1
PRINT "    Reading Thermocouples - - Please Wait."

'-----
' Set Constants For TC Polynomial.
'-----

A0# = .10086091#
A1# = 25727.94369#
A2# = -767345.8295#
A3# = 78025595.81#
A4# = -9247486589#
A5# = 697688000000#
A6# = -26619200000000#
A7# = 394078000000000#
' t = A2# + tc * (A3# + tc * (A4# + tc * (A5# + tc * (A6# + tc * A7#))))
' t = A0# + tc * (A1# + tc * (t))

'-----
' Set Gain Variable and DASH-8 Channel Numbers.
'-----

Gain% = 1000!

D81% = 6           ' DAS 8 Channel number for Thermocouples
D82% = 7           ' DAS 8 Channel for CJC

'-----
' Read the 6 Thermocouples and convert to Voltage.
'-----

FOR j% = 1 TO 6
  Sum% = 0
  FOR i% = 1 TO 20
    CALL readmux(D81%, (j% - 1), Bits%)
    Sum% = Sum% + Bits%
  NEXT i%
  tc(j%) = 5! * Sum% / 20 / 2048 / Gain%      'output of tc in Volts
NEXT j%

'-----
' Read the CJC Voltage and Convert it to Temperature.

```

```

-----
Sum% = 0
FOR i% = 1 TO 20
  CALL readmux(D82%, 0, Bits%)
  Sum% = Sum% + Bits%
NEXT i%
cjc = 5! * Sum% / 20 / 2048 / .0244           'cjc temp in Deg. C
-----

```

```

' Calculate the Equivalent EMF of a type T Thermocouple at the same
' temperature as the CJC circuit.
-----

```

```

mvestm = (cjc * .04) / 1000

DO
  t = A2# + mvestm * (A3# + mvestm * (A4# + mvestm * (A5# + mvestm * (A6# + mvestm * A7#))))
  t = A0# + mvestm * (A1# + mvestm * (t))
  IF t > cjc THEN
    mvestm = mvestm - .000002
  ELSE
    mvestm = mvestm + .000002
  END IF
LOOP UNTIL ABS(cjc - t) < .05
-----

```

```

' Calculate the temperature of the Thermocouples.
-----

```

```

FOR j% = 1 TO 6
  tc2 = tc(j%) + mvestm
  t = A2# + tc2 * (A3# + tc2 * (A4# + tc2 * (A5# + tc2 * (A6# + tc2 * A7#))))
  tempC(j%) = A0# + tc2 * (A1# + tc2 * (t))
  tempF(j%) = tempC(j%) * 1.8 + 32!
NEXT j%
-----

```

```
END SUB
```

```
SUB readvload (vforce(), z%)
```

```

*****
*****          SUBPROGRAM readvload          *****
*****
' * Calls READMUX 30 times for each of the vertical load cells,      *
' * calculates the average reading for each channel                    *
*
*****
-----

```

```

' Dimension Variables
-----

```

```
DIM AvgBits(8)
```

```

' Print Message for the Operator
-----

```

```

CLS
LOCATE 10, 5
PRINT "Reading Vertical Force Transducers - - PLEASE WAIT."
-----

```

```

' Call READMUX to read each channel 30 times then calculate the average
-----

```

```
FOR i% = 1 TO 8
```

```

Sum& = 0!
FOR j% = 1 TO 30
  CALL readmux(Vload(i%).DasChan, Vload(i%).ExpChan, Bits%)
  Sum& = Sum& + Bits%
NEXT
AvgBits(i%) = Sum& / 30!
NEXT

```

```

-----
' If this call is not for zero readings, subtract the zero readings
' and calculate the forces.
-----

```

```

IF z% <> 0 THEN
  FOR i% = 1 TO 8
    vforce(i%) = (AvgBits(i%) - Vload(i%).zero) * Vload(i%).Calib
  NEXT i%

```

```

-----
' If this call is for zero readings, record the readings
-----

```

```

ELSE
  FOR i% = 1 TO 8
    Vload(i%).zero = AvgBits(i%)
  NEXT i%
END IF
CLS

```

END SUB

SUB readzerofile

```

*****
*****          SUBPROGRAM readzerofile          *****
*****
'* Reads the Transducer Zero Readings From the Data File *
*****

```

```

-----
' Read zero readings from the file for the Gloetzl E. P. cells
-----

```

```

skip 2
FOR i% = 1 TO 11
  junk$ = INPUT$(12, 2)
  INPUT #2, Gloetzl(i%).zero, jnk
NEXT

```

```

-----
' Read zero readings from the file for the Carlson E. P. cells
-----

```

```

skip 2
FOR i% = 1 TO 4
  junk$ = INPUT$(12, 2)
  INPUT #2, Carlson(i%).zero, jnk, jnk
NEXT

```

```

-----
' Read zero readings from the file for the Geonor E. P. cells
-----

```

```

skip 2
FOR i% = 1 TO 1
  junk$ = INPUT$(12, 2)
  INPUT #2, Geonor(i%).zero, jnk
NEXT

```

```
-----  
' Read zero readings from the file for the horizontal load cells  
-----
```

```
skip 2  
FOR i% = 1 TO 12  
  junk$ = INPUT$(12, 2)  
  INPUT #2, Hload(i%).zero, jnk  
NEXT
```

```
-----  
' Read zero readings from the file for the vertical load cells  
-----
```

```
skip 2  
FOR i% = 1 TO 8  
  junk$ = INPUT$(12, 2)  
  INPUT #2, Vload(i%).zero, jnk  
NEXT
```

```
-----  
' Read zero readings from the file for the LVDTs  
-----
```

```
skip 2  
FOR i% = 1 TO 9  
  junk$ = INPUT$(12, 2)  
  INPUT #2, Lvdt(i%).zero  
NEXT
```

```
-----  
' Read zero readings from the file for the Thermocouples  
-----
```

```
skip 2  
FOR i% = 1 TO 6  
  junk$ = INPUT$(12, 2)  
  INPUT #2, TempZero(i%)  
NEXT
```

END SUB

SUB skip (filenum%)

```
*****  
***** SUBPROGRAM skip *****  
*****  
'* Performs line input from the specified file until a line with a "." *  
'* as the first non blank character is encountered *  
*****
```

```
DO  
  LINE INPUT #(filenum%), junk$  
  test$ = LEFT$(LTRIM$(junk$), 1)  
LOOP UNTIL test$ = "."
```

END SUB

SUB testdata

```
*****  
***** SUBPROGRAM testdata *****  
*****  
'* Record instrument readings to data file after subtracting zero *  
'* readings *  
*****
```

DIM hforce(12), vforce(8), pres(11), distance(14), Displ(9), tempF(10)

' Ask for test title and write title to file.

```
PRINT #2,  
PRINT #2,  
PRINT #2, "*****"  
PRINT #2, "*****"  
PRINT #2, *****  
PRINT #2, ***** TEST DATA SECTION *****  
PRINT #2, *****  
PRINT #2, "*****"  
PRINT #2, "*****"  
PRINT #2,  
CLS  
LOCATE 10, 5  
INPUT "Enter Title for this Phase of the Test : ", title$  
PRINT #2, "Title : "; title$  
PRINT #2,  
PRINT #2, "DATE : "; DATE$  
PRINT #2, "TIME : "; TIME$  
PRINT #2,  
PRINT #2,
```

' Take readings for Gloetzl cells and write them to file.

```
CALL readgloetzl(pres(), 1)  
  
PRINT #2, "-----"  
PRINT #2,  
PRINT #2, &&&&&&&&&&&& #####.##  
PRINT #2, "Gloetzl Earth "  
PRINT #2, "Inst. ID Pressure "  
PRINT #2, " (psi) "  
PRINT #2, ". "  
  
FOR i% = 1 TO 11  
PRINT #2, USING "& #####.##"; Gloetzl(i%).Label; pres(i%)  
NEXT i%  
PRINT #2,  
PRINT #2,
```

' Take readings for Carlson cells and write them to file.

```
CALL readcarlson(pres(), 1)  
  
PRINT #2, "-----"  
PRINT #2,  
PRINT #2, &&&&&&&&&&&& ##.## ##.##  
PRINT #2, "Carlson Earth Temp. "  
PRINT #2, "Inst. ID Pressure Reading "  
PRINT #2, " (psi) (Deg. F.) "  
PRINT #2, ". "  
  
FOR i% = 1 TO 4  
PRINT #2, USING "& ##.## ##.##"; Carlson(i%).Label; pres(i%); Carlson(i%).Temp  
NEXT i%  
PRINT #2,  
PRINT #2,
```

```
' Take readings for Geonor cells and write them to file.  
-----
```

```
CALL readgeonor(pres(), 1)  
PRINT #2, "-----"  
PRINT #2,  
      &&&&&&&&&&        #####  
PRINT #2, "Geonor      Earth    "  
PRINT #2, "Inst. ID     Pressure  "  
PRINT #2, "                (psi)    "  
PRINT #2, ". "  
  
FOR i% = 1 TO 1  
  PRINT #2, USING "&    ###.##"; Geonor(i%).Label; pres(i%)  
NEXT i%  
PRINT #2,  
PRINT #2,
```

```
' Take readings for horizontal load cells and write them to file.  
-----
```

```
CALL readhload(hforce(), 1)  
PRINT #2, "-----"  
PRINT #2,  
      &&&&&&&&&&&&&&&      #####.##  
PRINT #2, "H Load      Force    "  
PRINT #2, "Inst. ID      (lbs)    "  
PRINT #2, ". "  
  
FOR i% = 1 TO 12  
  PRINT #2, USING "&    #####.##"; Hload(i%).Label; hforce(i%)  
NEXT i%  
PRINT #2,  
PRINT #2,
```

```
' Take readings for vertical load cells and write them to file.  
-----
```

```
CALL readvload(vforce(), 1)  
PRINT #2, "-----"  
PRINT #2,  
      &&&&&&&&&&&&&&&      #####.##  
PRINT #2, "V Load      Force    "  
PRINT #2, "Inst. ID      (lbs)    "  
PRINT #2, ". "  
  
FOR i% = 1 TO 8  
  PRINT #2, USING "&    #####.##"; Vload(i%).Label; vforce(i%)  
NEXT i%  
PRINT #2,  
PRINT #2,
```

```
' Take readings for LVDTs and write them to file.  
-----
```

```
CALL readlvdt(Displ(), 1)  
PRINT #2, "-----"  
PRINT #2,  
      &&&&&&&&&&      ##.####  
PRINT #2, "LVDT      Displacement"  
PRINT #2, "Inst. ID  (inches)"  
PRINT #2, ". "
```

```

FOR i% = 1 TO 9
  PRINT #2, USING "&      ##.###"; LvdT(i%).Label; Disp1(i%)
NEXT i%
PRINT #2,
PRINT #2,
-----
' Take readings for Temperature and write them to file.
-----

CALL readtc(tempF())

PRINT #2, "-----"
PRINT #2,
      Tcouple #      ###.#      ###.#
PRINT #2, "Tcouple      Temperature      Change in "
PRINT #2, "Inst. ID      Reading      Temperature"
PRINT #2, "      (Deg. F)      (Deg. F)"
PRINT #2, "."

FOR i% = 1 TO 6
  PRINT #2, USING "Tcouple #      ###.#      ###.#"; i%; tempF(i%); (tempF(i%) -
TempZero(i%))
NEXT i%
PRINT #2,
PRINT #2,
END SUB

```

B.3 PROGRAM UDM2.BAS

B.3.1 Function of Program Segments

- 1) Main program UDM2.BAS does the following:
 - a) Declares the subprograms,
 - b) Defines the variables types,
 - c) Dimensions the array variables and identifies variables that are shared between the program segments,
 - d) Initializes program variables, computer settings, and data-acquisition hardware, and
 - e) Addresses the ultrasonic distance measuring system, obtains distance measurements, and writes the information to the data file and to the computer screen.

- 2) Subprogram ANYKEY delays the program until one of the keyboard keys is pressed.
- 3) Subprogram CONNECTIONS reads connection, location and calibration information from the file MASTER.ZZZ for each the instruments.
- 4) Subprogram MESSAGE instructs the operator to prepare the ultrasonic distance measurement system for the measurement cycle.
- 5) Subprogram PAUSE holds the program in a loop until the specified time interval has elapsed.
- 6) Subprogram READZEROFIELD reads the zero readings for each of the instruments from the data file.
- 7) Subprogram SKIP moves the file pointer in a file to the line following the next occurrence of a period as the first non-blank character on a line.

B.3.2 Listing of Program UDM2.BAS

```

*****
*****          PROGRAM UDM2.BAS          *****
*****
'* Program UDM2.BAS addresses the ultrasonic distance measurement system  *
'* and records the distance measurements.                                *
*****

-----
'   Declare Subroutines
-----

DECLARE SUB anykey ( )
DECLARE SUB connections (Lastfile$, ZorD$)
DECLARE SUB message ( )
DECLARE SUB pause (interval!)
DECLARE SUB readzerofile ( )
DECLARE SUB skip (filenum%)

-----
'   Define Types
-----

TYPE ud
  Label AS STRING * 6
  y AS SINGLE
  x AS SINGLE
  Zero AS SINGLE

```

END TYPE

' Dimension Variables

DIM SHARED UDM(1 TO 20) AS ud
COMMON SHARED path\$, er%, er\$, UdmRef, LocLastFileName%
DIM Distance(14), CountSum(14), NumGood%(14), MuxChan%(14)

' Set Screen Mode

SCREEN 2

' Initialize the UDM hardware.

CALL INIT

' Assign MUX channel numbers to the UDM instruments.

```
FOR i% = 1 TO 13
  IF i% >= 8 THEN
    MuxChan%(i%) = i% + 1
  ELSE
    MuxChan%(i%) = i%
  END IF
NEXT i%
```

' Read the transducer connection/location/calibration file.

CALL connections>Lastfile\$, ZorD\$)

' If This Cycle is to Measure Fill Thickness, Open the Data File and
' Read UDM Zero Values.

```
IF UCASE$(LEFT$(LTRIM$(ZorD$), 1)) = "D" THEN
  OPEN Lastfile$ FOR INPUT AS #2
  CALL readzerofile
  CLOSE #2
END IF
```

' Tell operator to prepare UDM system.

message

' Start of UDM observation loop.

DO

```
CLS
LOCATE 10, 5
PRINT "Reading Distances with UDM System - - PLEASE WAIT."
```

' Zero the sum and count variables.

```
FOR i% = 1 TO 13
  CountSum(i%) = 0!
  NumGood%(i%) = 0
NEXT i%
```

' Try to read each UDM 10 times.

```
FOR j% = 1 TO 10
  FOR i% = 1 TO 13
    CALL CHANNEL(MuxChan%(i%))      'MEASUREMENT LOOP
    CALL CHANNEL(MuxChan%(i%))      'set channel
    pause .01                        'pause 0.01 second
    T1! = TIMER
    DO
      CALL PULSE                      'pulse the UDM
      CALL RangeCount(range%)        'listen for echo
      Dt! = TIMER - T1!
    LOOP UNTIL range% > 0 OR Dt! > 2!
    IF range% > 225 AND range% < 4000 AND i% < 13 THEN
      CountSum(i%) = CountSum(i%) + range%
      NumGood%(i%) = NumGood%(i%) + 1
    ELSEIF range% > 2680 AND range% < 2780 AND i% = 13 THEN
      CountSum(i%) = CountSum(i%) + range%
      NumGood%(i%) = NumGood%(i%) + 1
    END IF
  NEXT i%
NEXT j%
```

```
Factor = CountSum(13) / NumGood%(13) / 44.8 / 62.71
Distance(13) = CountSum(13) / NumGood%(13) / 44.8
```

' Based on information read from the file MASTER.ZZZ, (IF) record zero
' readings or (ELSE) record distance data.

```
IF UCASE$(LEFT$(LTRIM$(ZorD$), 1)) = "Z" THEN
```

' Calculate Distances and Display Them.

```
CLS
FOR i% = 1 TO 12
  Distance(i%) = CountSum(i%) / NumGood%(i%) / 44.8 / Factor
  PRINT USING " UDM ## Measures ###.## Inches Based on ## Observations"; i%;
Distance(i%); NumGood%(i%)
NEXT i%
```

' Present Operator with the options.

```
PRINT
PRINT
PRINT " YOUR OPTIONS ARE : "
PRINT
PRINT " 1.) Accept Measurements, Write Then to File, and Quit."
PRINT " 2.) Remeasure, Display New Measurements, and Have These Options Again."
PRINT
PRINT " MAKE SELECTION BY NUMBER : ";
```

```

DO
  Opt$ = INKEY$
  LOOP UNTIL Opt$ = "1" OR Opt$ = "2"
  CLS

  IF Opt$ = "1" THEN

```

```

-----
'   Write headers for UDM zero readings.
-----

```

```

  OPEN Lastfile$ FOR APPEND AS #2
  PRINT #2, "-----"
  PRINT #2,
  PRINT #2,      &&&&&&&      ##.##
  PRINT #2, "UDM          Zero"
  PRINT #2, "Inst. ID     Reading"
  PRINT #2, "              (inches)"
  PRINT #2, ". "

```

```

-----
'   Write distance zero readings to file.
-----

```

```

  FOR i% = 1 TO 12
    PRINT #2, USING "&      ##.##"; UDM(i%).Label; Distance(i%)
  NEXT i%
  PRINT #2,
  PRINT #2,
  CLOSE #2

```

```

END IF

```

```

-----
'   ELSEIF UCASE$(LEFT$(LTRIM$(ZorD$), 1)) = "D" THEN
-----

```

```

'   Calculate Fill Thicknesses and Display Them.
-----

```

```

  CLS
  FOR i% = 1 TO 12
    Distance(i%) = UDM(i%).Zero - CountSum(i%) / NumGood%(i%) / 44.8 / Factor
    PRINT USING "  UDM ## Measures ###.## Inches of Fill Based on ## Observations"; i%;
Distance(i%); NumGood%(i%)
  NEXT i%
  PRINT USING "  UDM 13 Measures ###.## Inches Based on ## Observations"; Distance(13);
NumGood%(13)
  PRINT
  PRINT USING "  The Adjustment Factor is #.####"; (1 / Factor)

```

```

-----
'   Present Operator with the options.
-----

```

```

  PRINT
  PRINT
  PRINT "  YOUR OPTIONS ARE :"
  PRINT
  PRINT "    1.) Accept Measurements, Write Then to File, and Quit."
  PRINT "    2.) Remeasure, Display New Measurements, and Have These Options Again."
  PRINT "    3.) Quit WITHOUT Recording Measurements."
  PRINT
  PRINT "  MAKE SELECTION BY NUMBER : ";
  DO

```

```

Opt$ = INKEY$
LOOP UNTIL Opt$ = "1" OR Opt$ = "2" OR Opt$ = "3"
CLS

IF Opt$ = "1" THEN

```

```

-----
' Write header for UDM zero readings.
-----

```

```

OPEN Lastfile$ FOR APPEND AS #2
PRINT #2, "-----"
PRINT #2,
      &&&&&&      ###.##
PRINT #2, "UDM      Fill"
PRINT #2, "Inst. ID  Thickness"
PRINT #2, "          (inches)"
PRINT #2, "."

```

```

-----
' Write fill thickness to file.
-----

```

```

FOR i% = 1 TO 12
  PRINT #2, USING "&      ###.##"; UDM(i%).Label; Distance(i%)
NEXT i%
PRINT #2,
PRINT #2,

CLOSE #2

```

```

-----
' If Operator Selected Option 3 ask for confirmation.
-----

```

```

ELSEIF Opt$ = "3" THEN
  PRINT
  PRINT
  PRINT " Are You Sure You Want to QUIT WITHOUT RECORDING MEASUREMENTS? (Y or N)"
  DO
    Optyn$ = UCASE$(INKEY$)
    LOOP UNTIL Optyn$ = "Y" OR Optyn$ = "N"
  CLS
  IF Optyn$ = "N" THEN
    Opt$ = "2"
  END IF
END IF
END IF

```

```

-----
LOOP UNTIL Opt$ <> "2"

```

```

END

```

```

SUB anykey

```

```

*****
*****          SUBPROGRAM anykey          *****
*****
'* Waits until the user presses a key on the keyboard. *
*****

```

```

DO
  LOOP WHILE INKEY$ = ""

```

```

END SUB

```

SUB connections (Lastfile\$, ZorD\$)

```
*****
*****          SUBPROGRAM connections          *****
*****
'   Opens the file MASTER.ZZZ and reads the connection and location   *
'   information for the UDM transducers.                               *
*****

-----
'   Open MASTER.ZZZ for input
-----

OPEN "MASTER.ZZZ" FOR INPUT AS #1

-----
'   Skip to section containing the UDM information.
-----

FOR i% = 1 TO 6
  skip 1
NEXT i%

-----
'   Read information for distance measuring transducers
'   Udm(i).Label = Label for UDM sensor i
'   Udm(i).x     = X coordinate for UDM sensor i
'   Udm(i).y     = Y coordinate for UDM sensor i
-----

FOR i = 1 TO 12
  INPUT #1, UDM(i).Label, UDM(i).x, UDM(i).y
NEXT i

-----
'   Skip to name of last file used by program EP.BAS
-----

FOR i% = 1 TO 4
  skip 1
NEXT i%

-----
'   Read name of last file used by program EP.BAS
-----

INPUT #1, Lastfile$

-----
'   Check if this step is to record zero readings or record test data
-----

INPUT #1, ZorD$

-----
'   Close file MASTER.ZZZ
-----

CLOSE #1

END SUB

SUB message
*****
*****          SUBPROGRAM message          *****
*****
'* Tell Operator to Prepare the UDM System and Wait Until a Key is Pressed *
*****
```

```

CLS
LOCATE 10, 1
PRINT "   Prepare Distance Measuring System "
PRINT
PRINT "   Check Power Switch on CONTAQ Multiplexer System"
PRINT
PRINT
PRINT "   Press Any Key to Continue"

CALL anykey

END SUB

SUB pause (interval)
'*****
'*****          SUBPROGRAM pause          *****
'*****
'* Program will remain in this subroutine for INTERVAL seconds then      *
'* return to the calling routine                                          *
'*****
  TO = TIMER

  DO
    Dt = TIMER - TO
  LOOP WHILE Dt < interval

END SUB

SUB readzerofile
'*****
'*****          SUBPROGRAM readzerofile    *****
'*****
'* Read UDM Zero Readings From the Data File.                            *
'*****

'-----
'  Skip to section with zero readings for the UDM instruments
'-----

  FOR i% = 1 TO 8
    skip 2
  NEXT i%

'-----
'  Read zero readings from the file for the UDM transducers
'-----

  FOR i% = 1 TO 12
    junk$ = INPUT$(12, 2)
    INPUT #2, UDM(i%).Zero
  NEXT

END SUB

SUB skip (filenum%)
'*****
'*****          SUBPROGRAM skip           *****
'*****
'* Performs line input from the specified file until a line with a "."   *
'* as the first non blank character is encountered                        *
'*****
  DO
    LINE INPUT #(filenum%), junk$
    test$ = LEFT$(LTRIM$(junk$), 1)
  LOOP UNTIL test$ = "."
END SUB

```

B.4 LISTING OF FILE MASTER.ZZZ

Inst. Ident.	Y Coord.	Z Coord.	DAS-8 Chan.	EXP-16 Chan.	Calib. bits/psi
Gloetzl 1 ,	66.5	70.0	2	0	51.7634
Gloetzl 2 ,	53.5	64.0	2	1	51.8166
Gloetzl 3 ,	66.5	58.0	2	2	51.7227
Gloetzl 4 ,	53.5	52.0	2	3	51.8335
Gloetzl 5 ,	66.5	46.0	2	4	51.3722
Gloetzl 6 ,	53.5	40.0	2	5	52.5673
Gloetzl 7 ,	66.5	34.0	2	6	52.1097
Gloetzl 8 ,	53.5	28.0	2	7	52.2506
Gloetzl 9 ,	66.5	22.0	2	8	50.3064
Gloetzl 10 ,	53.5	16.0	2	9	52.3043
Gloetzl 11 ,	66.5	10.0	2	10	51.8554

Inst. Ident.	Y Coord.	Z Coord.	DAS-8 Chan.	EXP-16 Chan1	EXP-16 Chan4	CTM-05 Dio	RES at zero Deg. F	Deg/ Ohm	Cnst	Rat0	Drat	Calib Carlson/ true
Carlson 1 ,	38.75	58	5	6	14	6	71.19	7.91	0.076	100.35	0.0055	0.9751
Carlson 2 ,	81.25	40	5	0	12	0	71.40	7.89	0.075	101.81	0.0062	0.9942
Carlson 3 ,	38.75	22	5	9	15	9	71.25	7.91	0.079	101.24	0.0060	0.8768
Carlson 4 ,	81.25	22	5	3	13	3	71.13	7.92	0.073	101.18	0.0065	0.9800

Inst. Ident	Y Coord.	Z Coord.	CTM-5 Chan.	Calib. Hz/psi
Geonor 1 ,	81.25	58	1	13.288
Geonor 2 ,	38.75	40	2	1.000

Load Cell	DAS-8 Chan.	EXP-16 Chan.	Calib. lbs/bit
H Load 1 ,	0	0	8.050
H Load 2 ,	0	1	8.026
H Load 3 ,	0	2	8.058
H Load 4 ,	0	3	8.051
H Load 5 ,	0	4	8.034
H Load 6 ,	0	5	8.045
H Load 7 ,	0	8	8.055
H Load 8 ,	0	9	8.043
H Load 9 ,	0	10	8.005
H Load 10 ,	0	11	7.889
H Load 11 ,	0	12	8.076
H Load 12 ,	0	13	8.080

V Load 1 ,	1	0	2.167
V Load 2 ,	1	1	2.189
V Load 3 ,	1	2	2.184
V Load 4 ,	1	3	2.181
V Load 5 ,	1	4	2.160
V Load 6 ,	1	5	2.193
V Load 7 ,	1	6	2.177
V Load 8 ,	1	7	2.163

Inst. Ident.	X Coord.	Y Coord.
UDM 1.	6.0	6.0
UDM 2.	36.0	6.0
UDM 3.	66.0	6.0
UDM 4.	6.0	42.0
UDM 5.	36.0	42.0
UDM 6.	66.0	42.0
UDM 7.	6.0	78.0
UDM 8.	36.0	78.0
UDM 9.	66.0	78.0
UDM 10.	6.0	114.0
UDM 11.	36.0	114.0
UDM 12.	66.0	114.0

Displ. Trans.	Y Coord.	Z Coord.	DAS-8 Chan.	EXP-16 Chan.
LVDT 1.	15.0	6.5	3	0
LVDT 2.	15.0	75.0	3	1
LVDT 3.	45.0	6.5	3	2
LVDT 4.	45.0	75.0	3	3
LVDT 5.	75.0	6.5	3	4
LVDT 6.	75.0	75.0	3	5
LVDT 7.	105.0	6.5	3	6
LVDT 8.	105.0	75.0	3	7
LVDT 9.	105.0	75.0	3	8

LVDT Calibration Information

Bits at +0.500"	Bits at +0.400"	Bits at +0.300"	Bits at +0.200"	Bits at +0.100"	Bits at 0.000"	Bits at -0.100"	Bits at -0.200"	Bits at -0.300"	Bits at -0.400"	Bits at -0.500"
1075.73	863.09	649.25	433.90	219.33	-0.60	-221.28	-442.87	-667.57	-892.57	-1115.73
1088.40	867.62	654.20	434.22	217.50	-0.44	-220.05	-439.62	-660.78	-877.84	-1097.43
1125.04	896.99	670.45	444.95	221.52	-2.00	-224.49	-445.74	-668.39	-890.65	-1113.97
1095.94	875.30	654.65	433.82	216.80	-2.39	-222.38	-442.44	-666.40	-891.40	-1116.30
1089.75	872.52	655.35	436.74	218.34	-0.92	-222.05	-444.84	-669.00	-894.04	-1118.30
1095.90	877.88	659.50	440.35	221.87	0.89	-221.15	-443.80	-668.20	-892.34	-1117.77
1129.17	900.39	672.49	444.24	221.07	-2.27	-225.29	-448.55	-673.27	-897.72	-1124.03
1102.00	883.75	664.32	443.62	222.94	-0.10	-224.45	-449.52	-675.72	-903.55	-1131.40

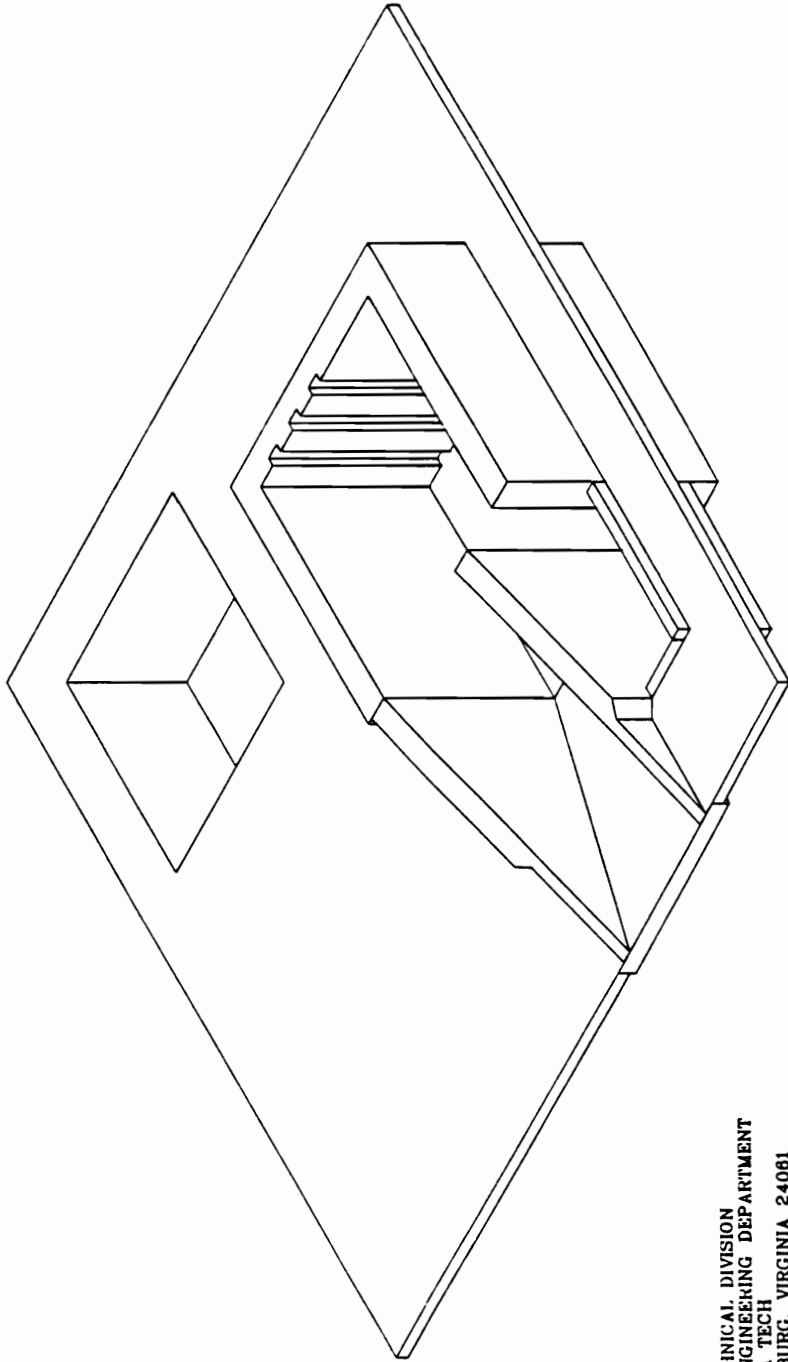
Bits at +0.100"	Bits at +0.080"	Bits at +0.060"	Bits at +0.040"	Bits at +0.020"	Bits at 0.000"	Bits at -0.020"	Bits at -0.040"	Bits at -0.060"	Bits at -0.080"	Bits at -0.100"
1012.63	812.42	612.03	409.96	206.16	2.61	-199.91	-402.13	-603.75	-802.38	-999.75

Last Output Filename

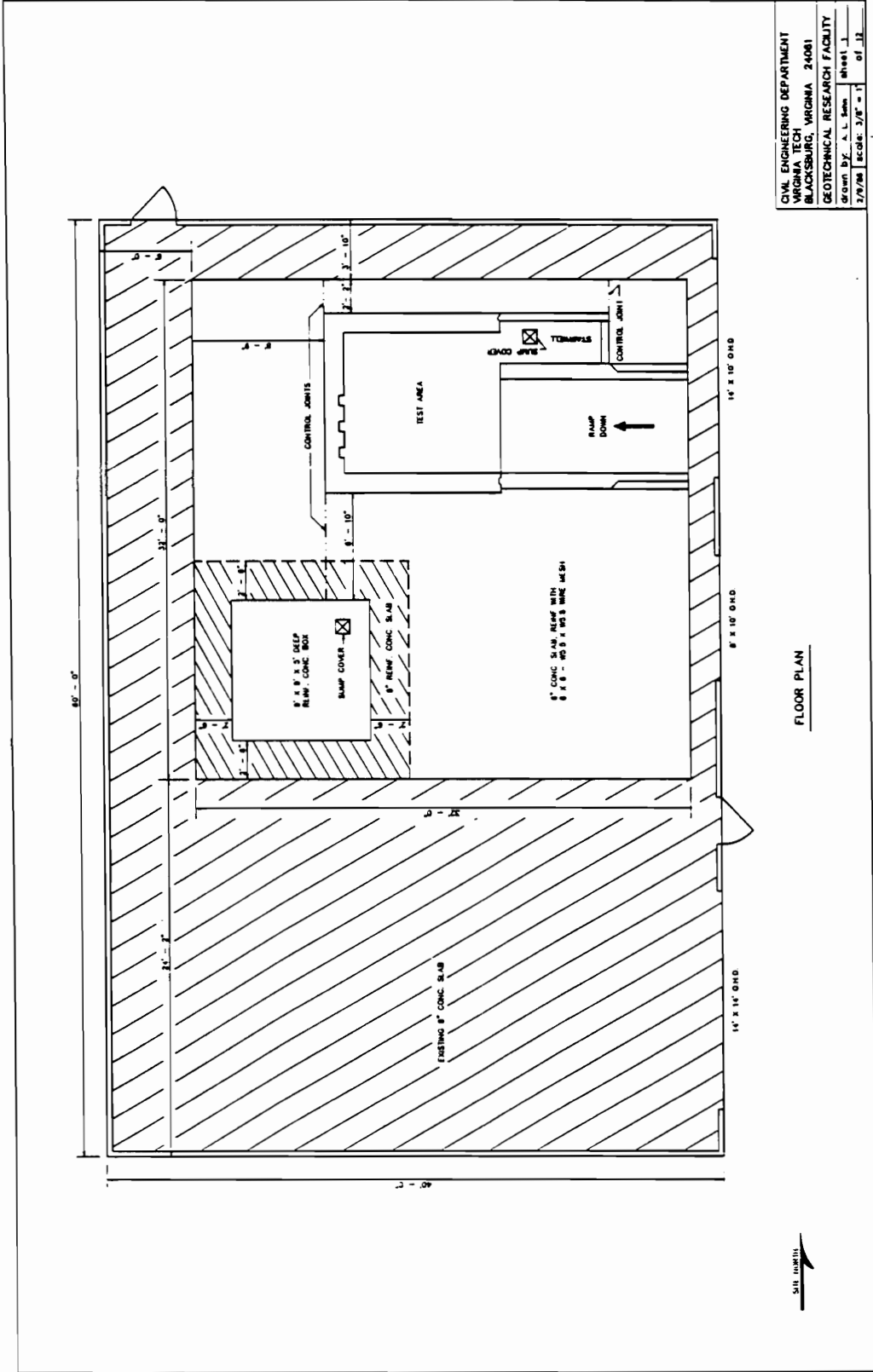
TRIAL1.EPD
DATA

APPENDIX C
CONSTRUCTION AND MACHINE SHOP DRAWINGS
FOR THE INSTRUMENTED RETAINING WALL FACILITY

GEOTECHNICAL RESEARCH FACILITY



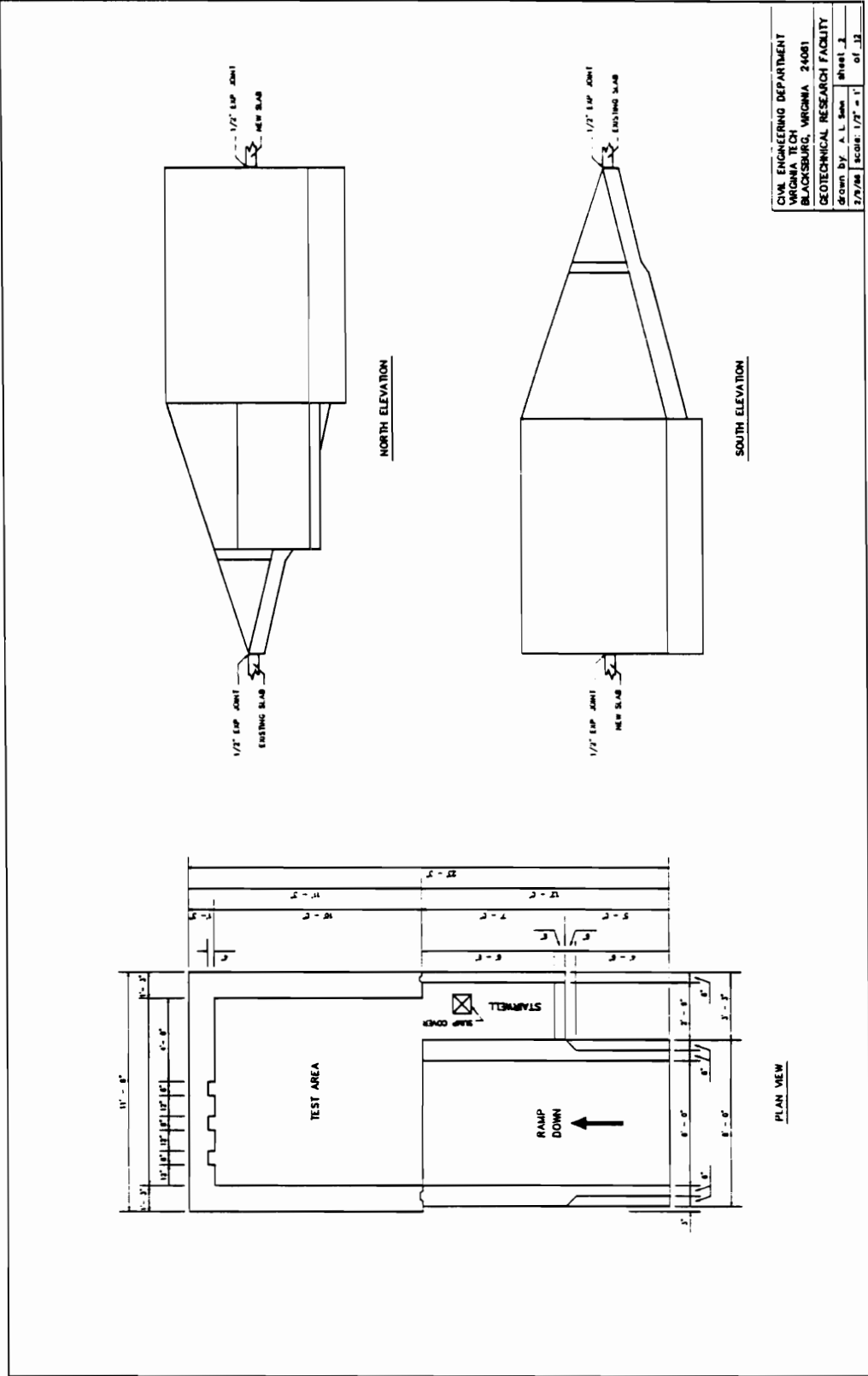
**GEOTECHNICAL DIVISION
CIVIL ENGINEERING DEPARTMENT
VIRGINIA TECH
BLACKSBURG, VIRGINIA 24061**



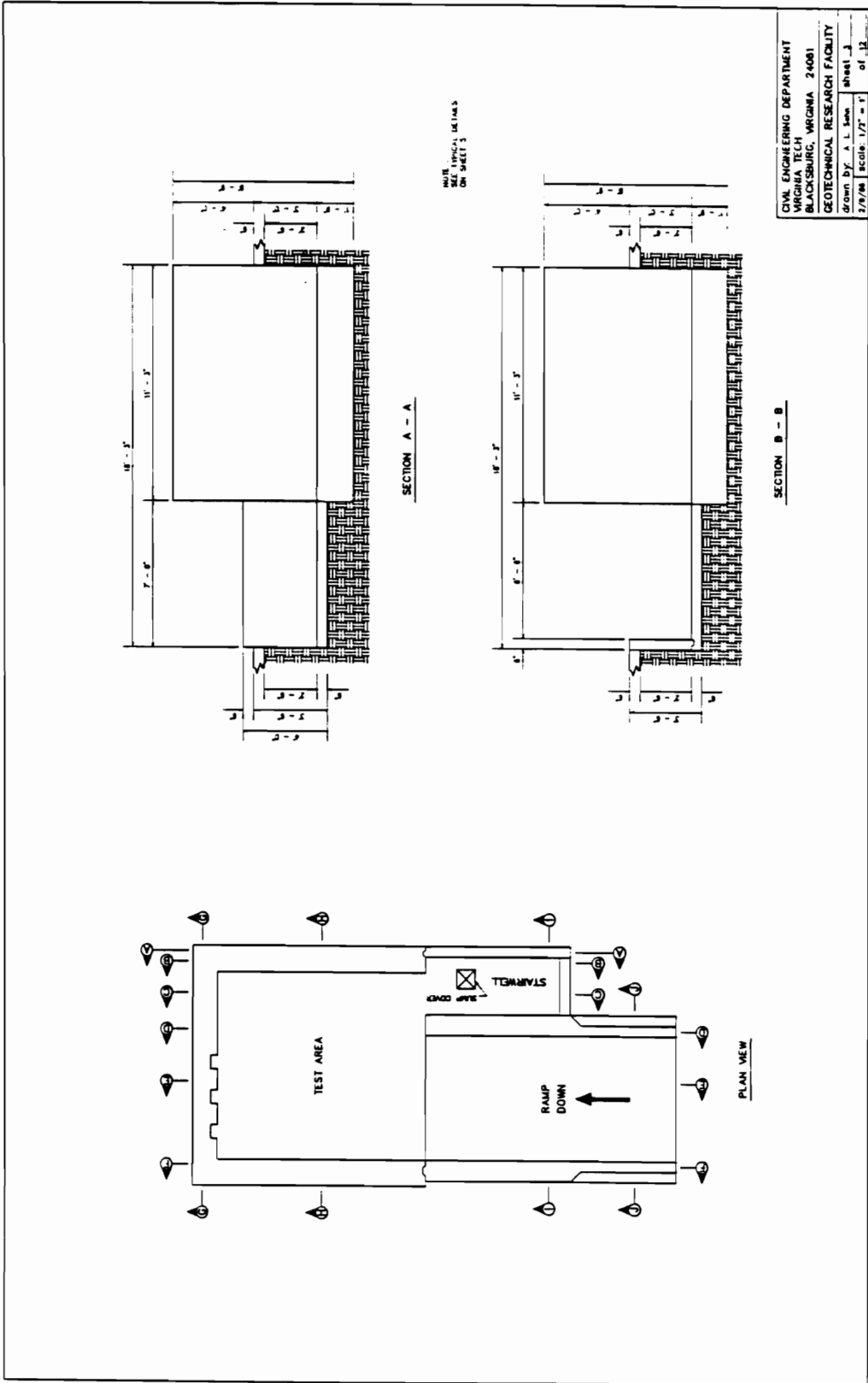
CIVIL ENGINEERING DEPARTMENT
 VIRGINIA TECH
 BLACKSBURG, VIRGINIA 24061
 GEOTECHNICAL RESEARCH FACILITY
 Drawn BY: A. L. Mann sheet 1
 3/7/78 scale: 3/8" = 1' of 11

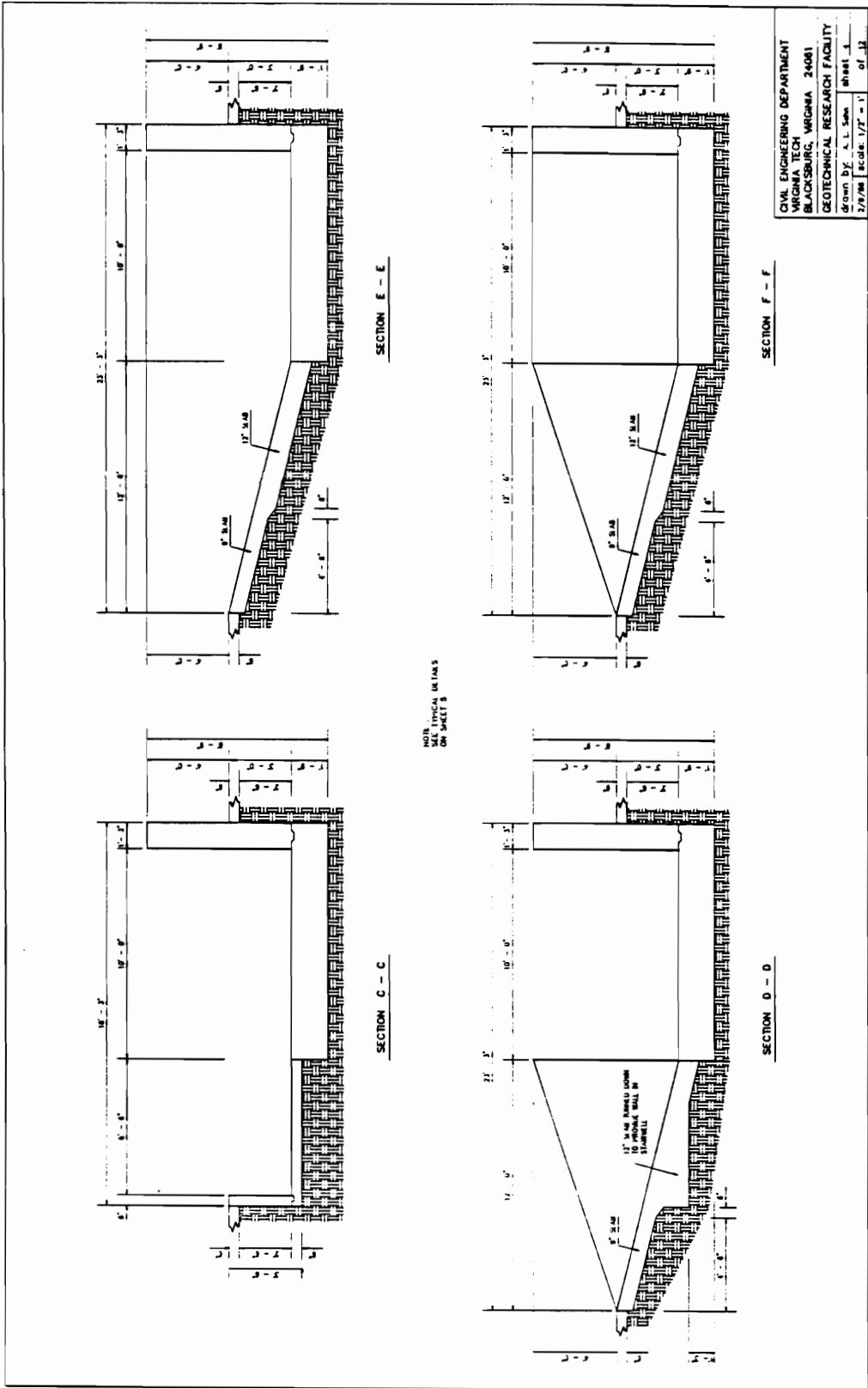
FLOOR PLAN

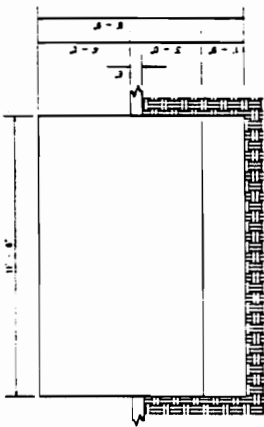




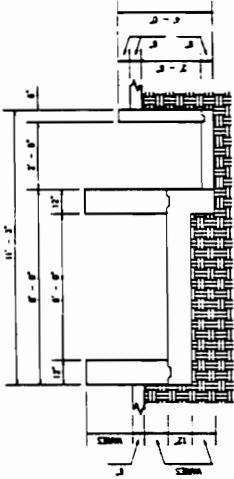
CIVIL ENGINEERING DEPARTMENT		
VIRGINIA TECH		
BLACKSBURG, VIRGINIA 24061		
GEOTECHNICAL RESEARCH FACILITY		
drawn by	A. L. Sells	Sheet 3
2/7/68	Scale: 1/2" = 1'	of 31



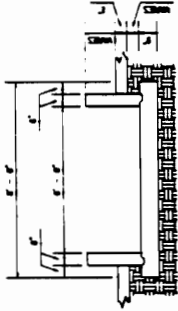




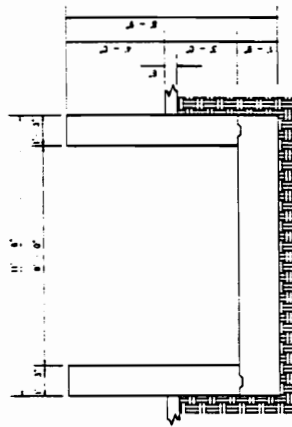
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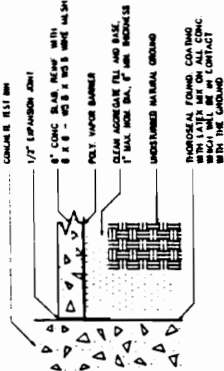
SECTION I - I
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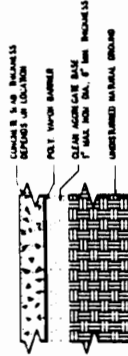
SECTION J - J
SCALE 1/2" = 1'



SECTION H - H
SCALE 1/2" = 1'

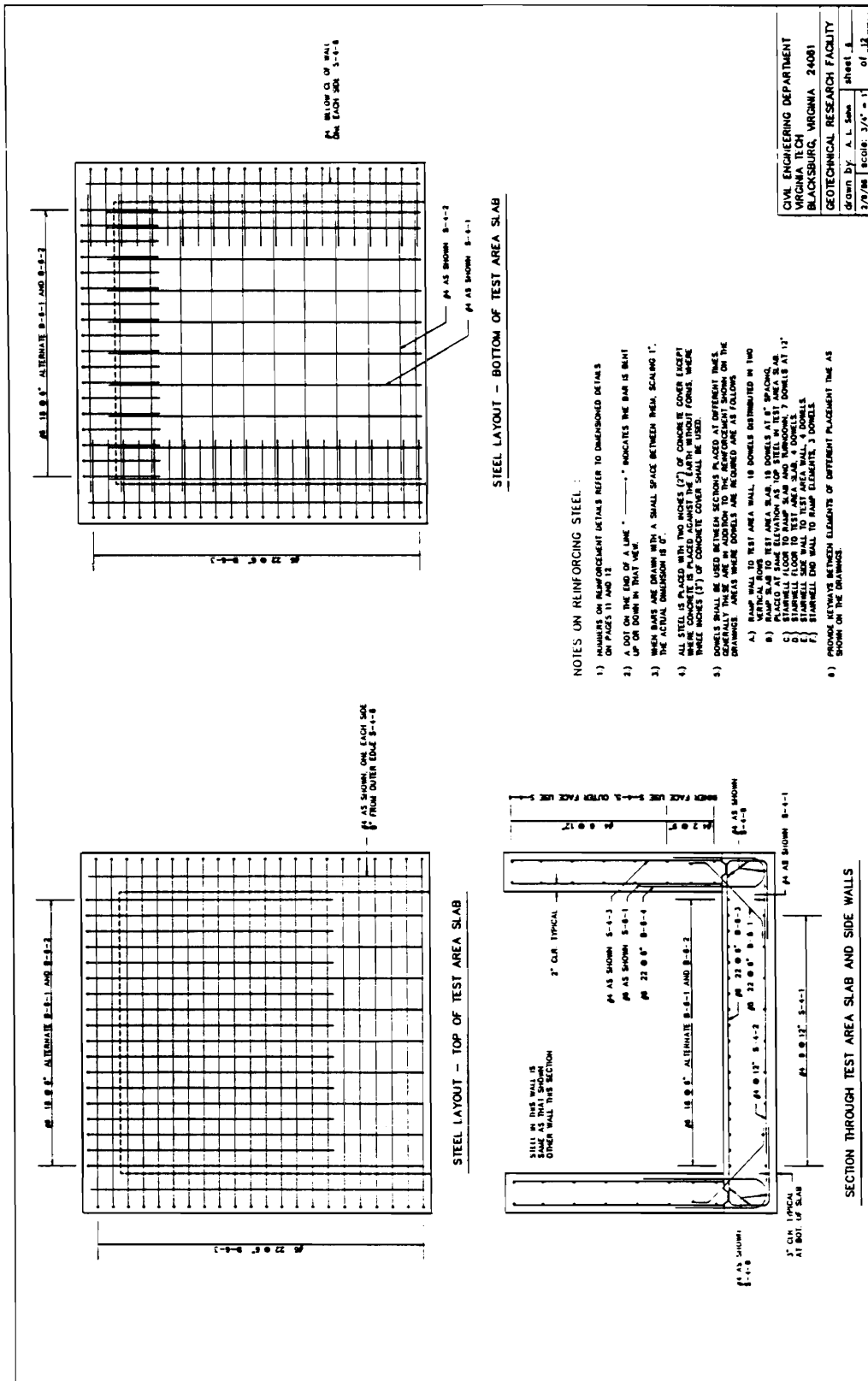


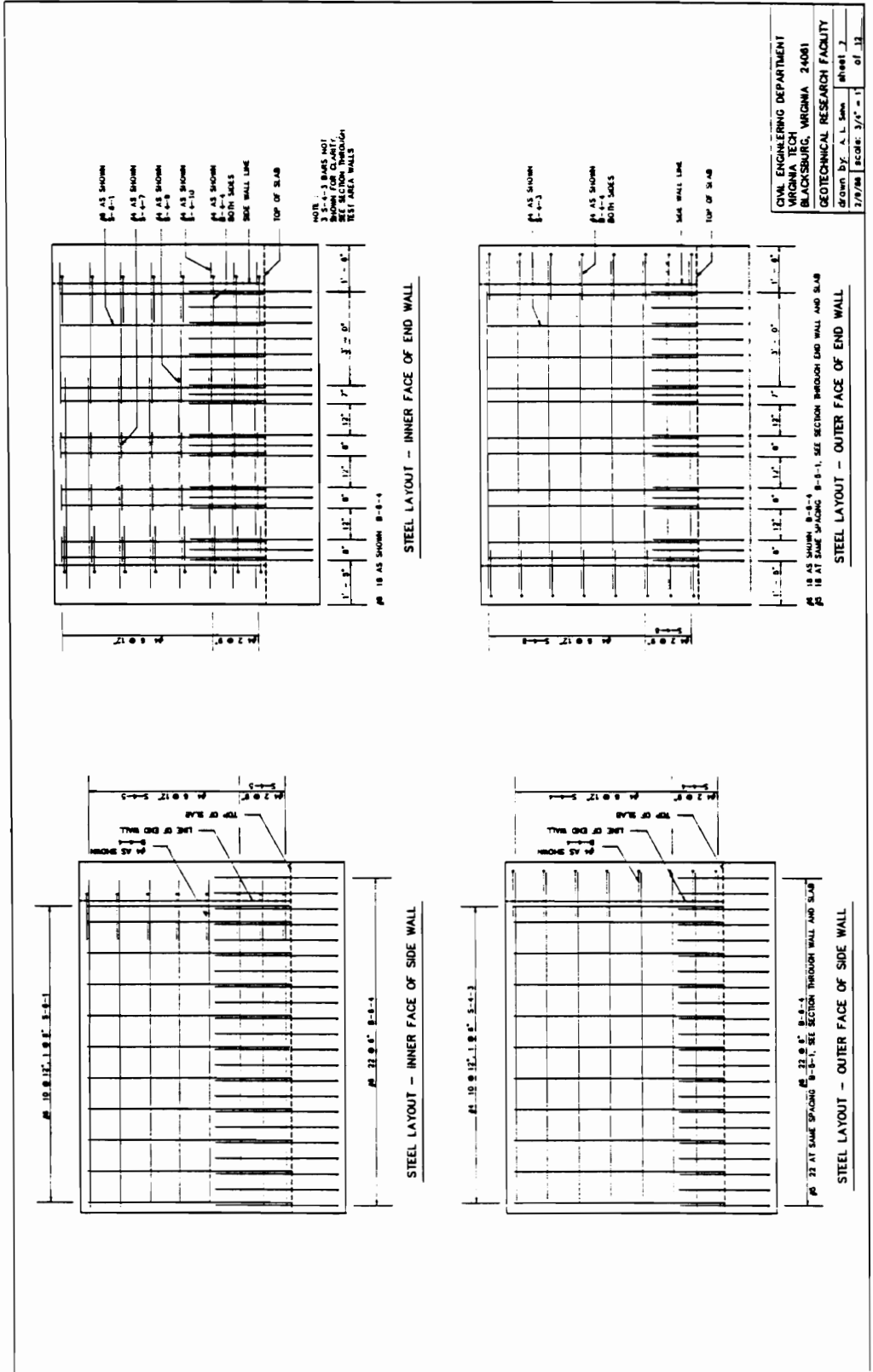
TYPICAL JOINT DETAIL, FLOOR SLAB AT TEST BM
SCALE 1" = 1'



TYPICAL BASE DETAIL, ALL SLABS
SCALE 1" = 1'

CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF VIRGINIA
BLACKSBURG, VIRGINIA 24061
GEOTECHNICAL RESEARCH FACILITY
drawn by A. L. Soren
1/7/76
sheet 3
scale as noted of 12

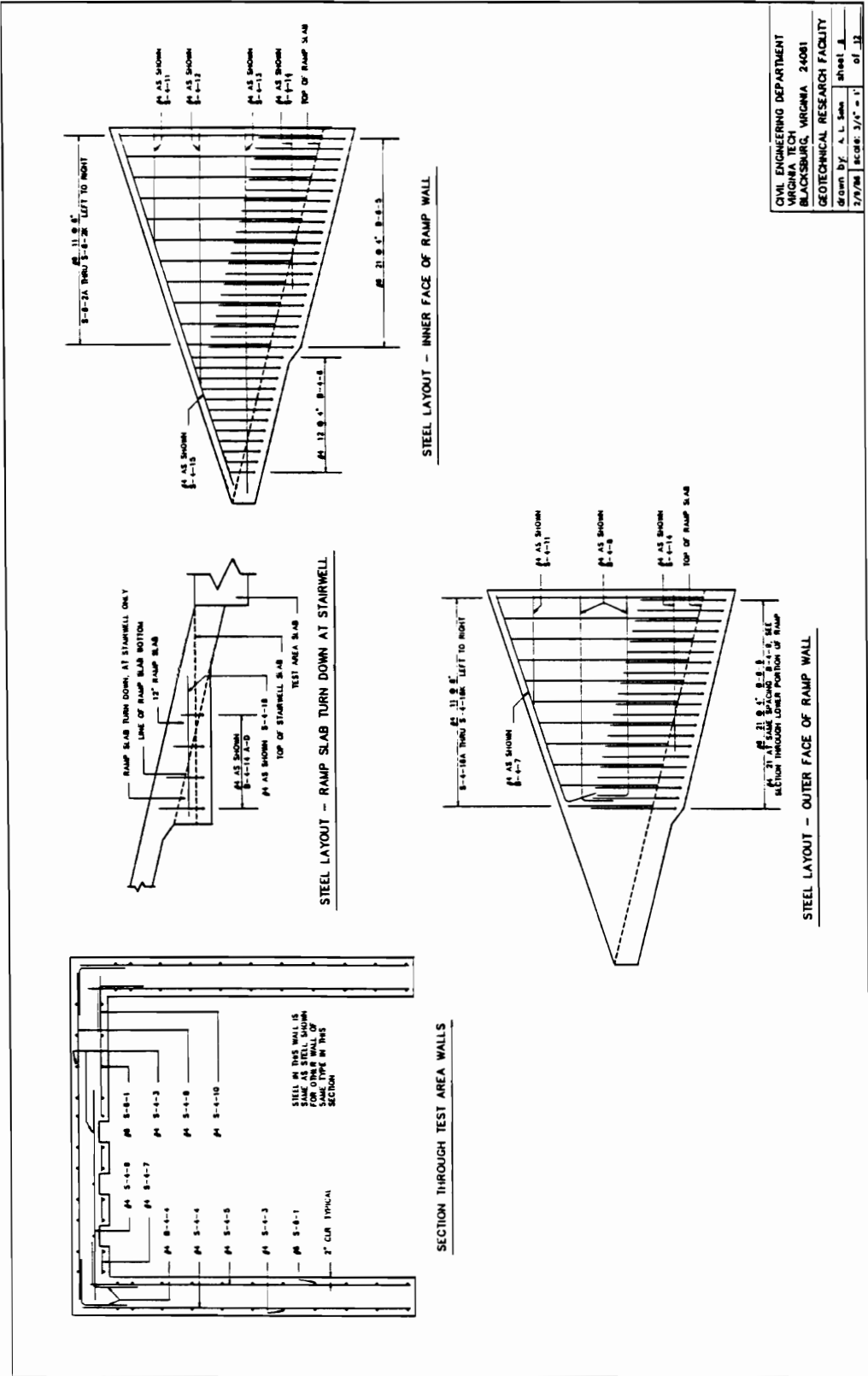


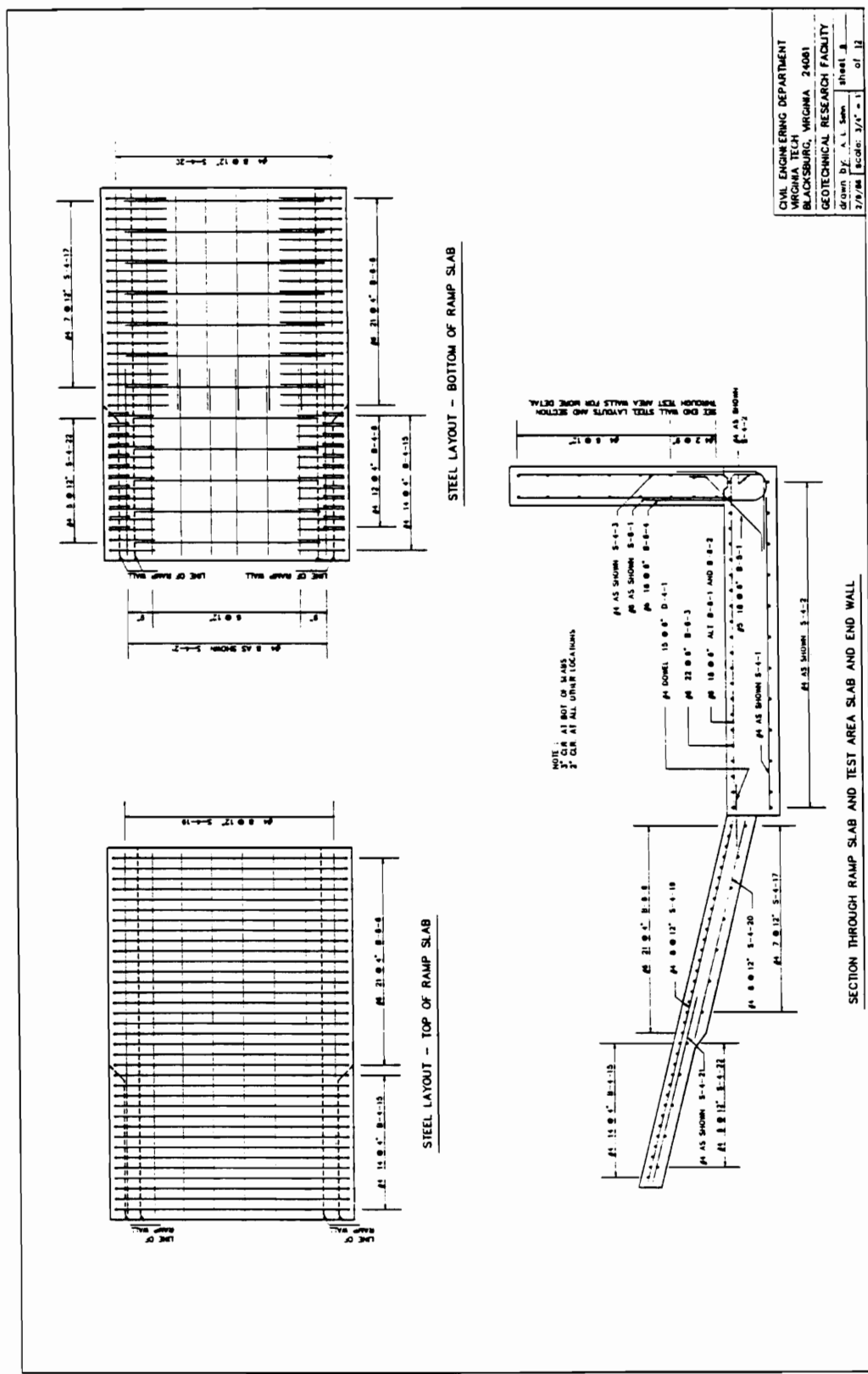


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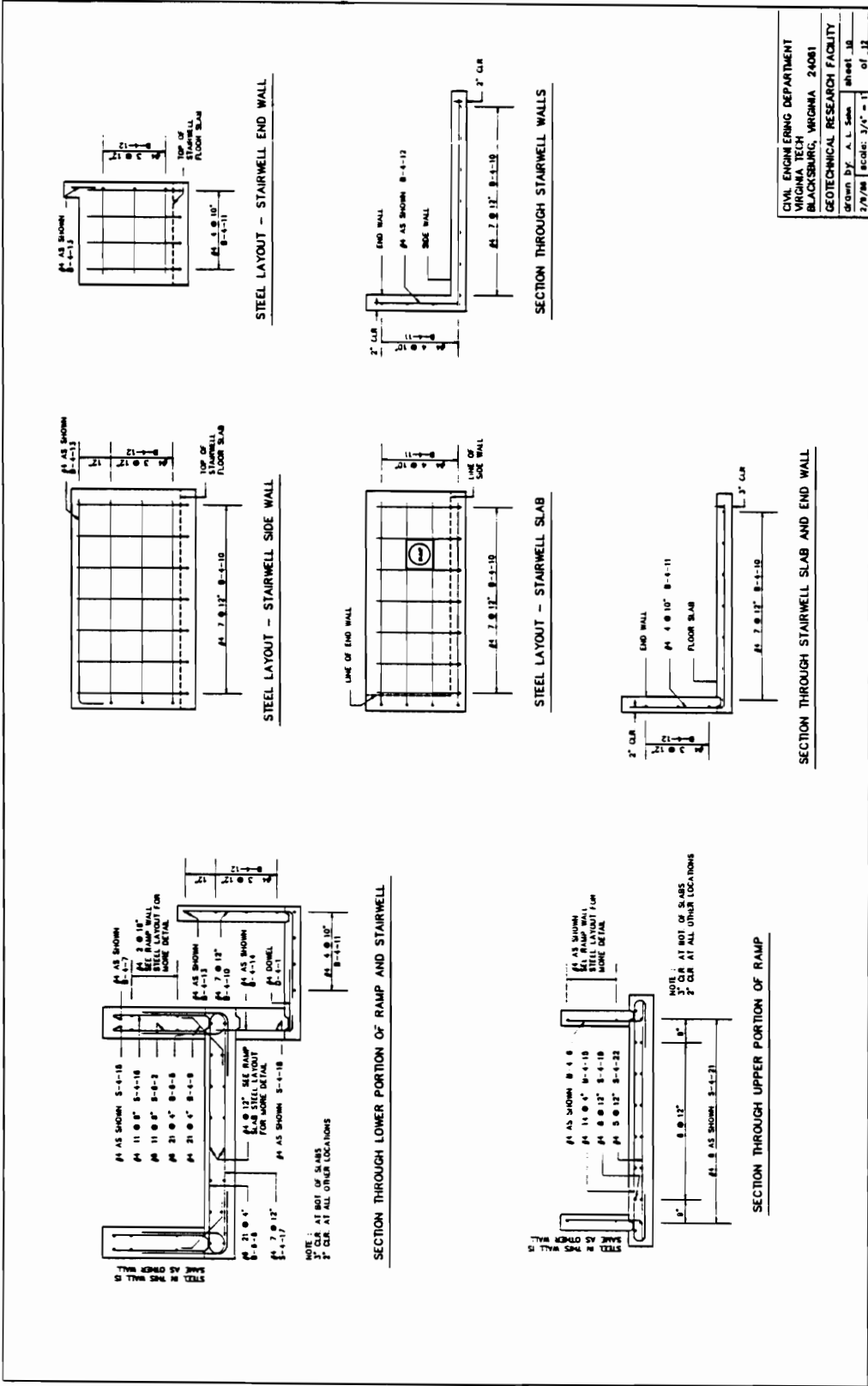
Drawn by: A. L. Sams
 2/7/78
 Scale: 3/4" = 1'

Sheet 2 of 12





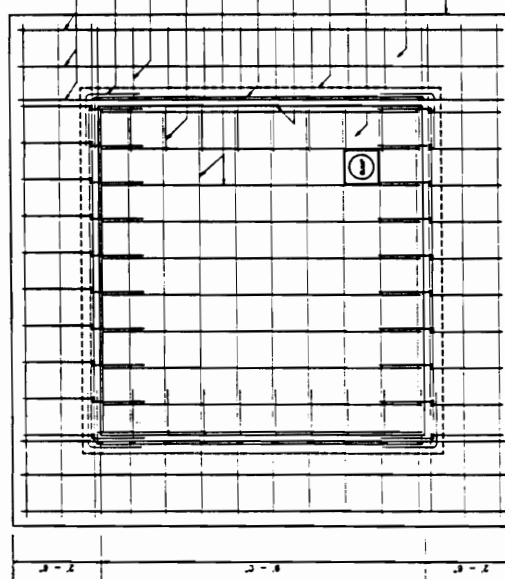
CIVIL ENGINEERING DEPARTMENT
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 GEOTECHNICAL RESEARCH FACILITY
 Drawn by: A. I. Senn sheet 8
 3/8/86 scale: 3/4" = 1' of 12



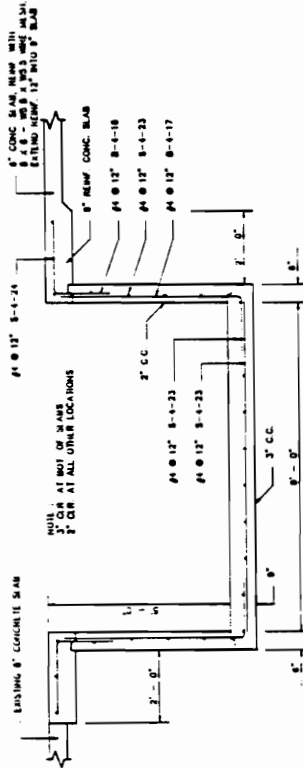
CIVIL ENGINEERING DEPARTMENT
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 BLACKSBURG, VIRGINIA 24081
 GEOTECHNICAL RESEARCH FACILITY
 drawn by: A. L. Searl Sheet 10
 2/9/88 Scale: 3/4" = 1' of 12

NOTE: PRECAST CONCRETE IS A CONSTRUCTION OPTION FOR THE WALLS AND SLAB PORTIONS OF THE DESIGN IS REQUIRED. THE METHOD OF DESIGN IS REQUIRED.

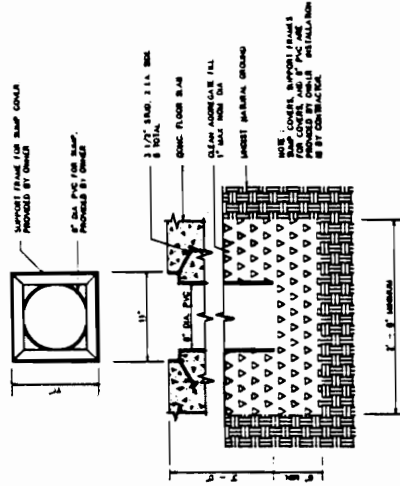
#4 @ 12" S-4-24
#4 @ 12" S-4-18
#4 @ 12" S-4-18
#4 @ 12" S-4-17
#4 @ 12" S-4-23
#4 @ 12" S-4-23
#4 @ 12" S-4-23
INSIDE FACE OF WALL
OUTSIDE FACE OF WALL
#4 SLAB AT BOTTOM OF BOX
#4 APRON SLAB AROUND BOX
LINE OF TRANSITION FROM #4 APRON TO #4 SLAB



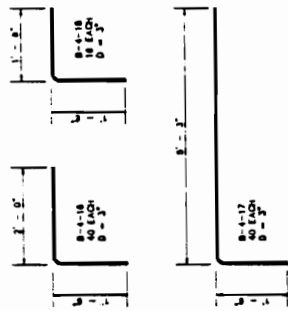
STEEL LAYOUT - CONCRETE BOX AND APRON
SCALE: 3/4" = 1'



SECTION THROUGH CONCRETE BOX AND APRON
SCALE: 3/4" = 1'

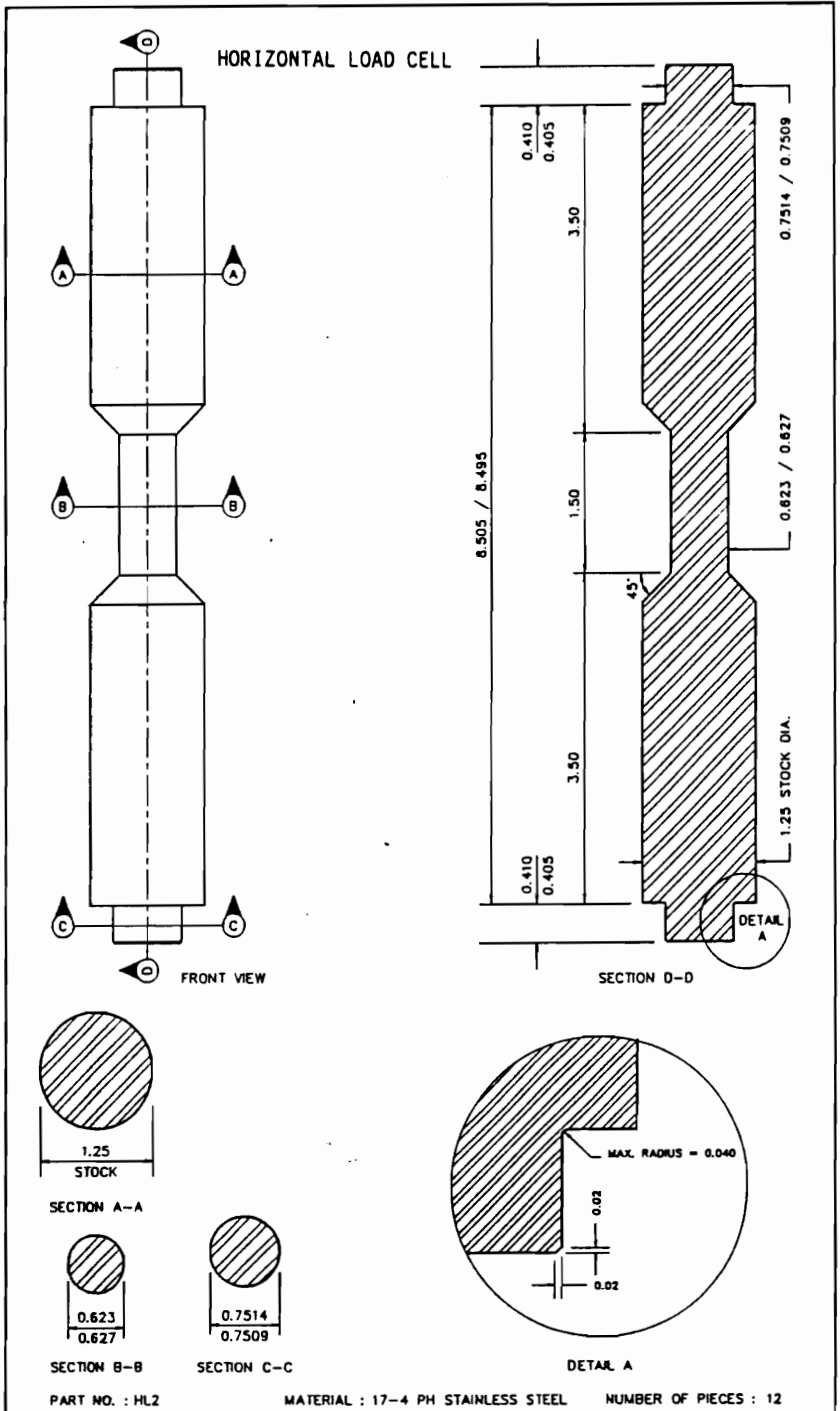


DETAIL OF SUMP
SCALE: 3/4" = 1'



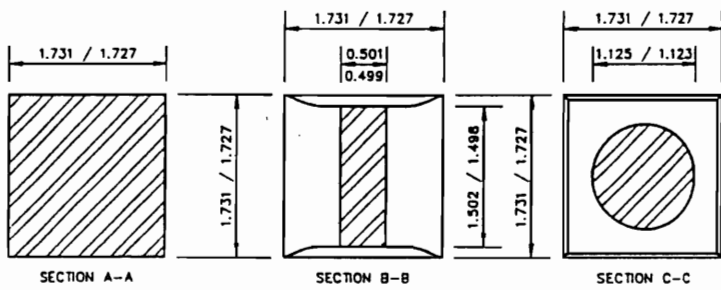
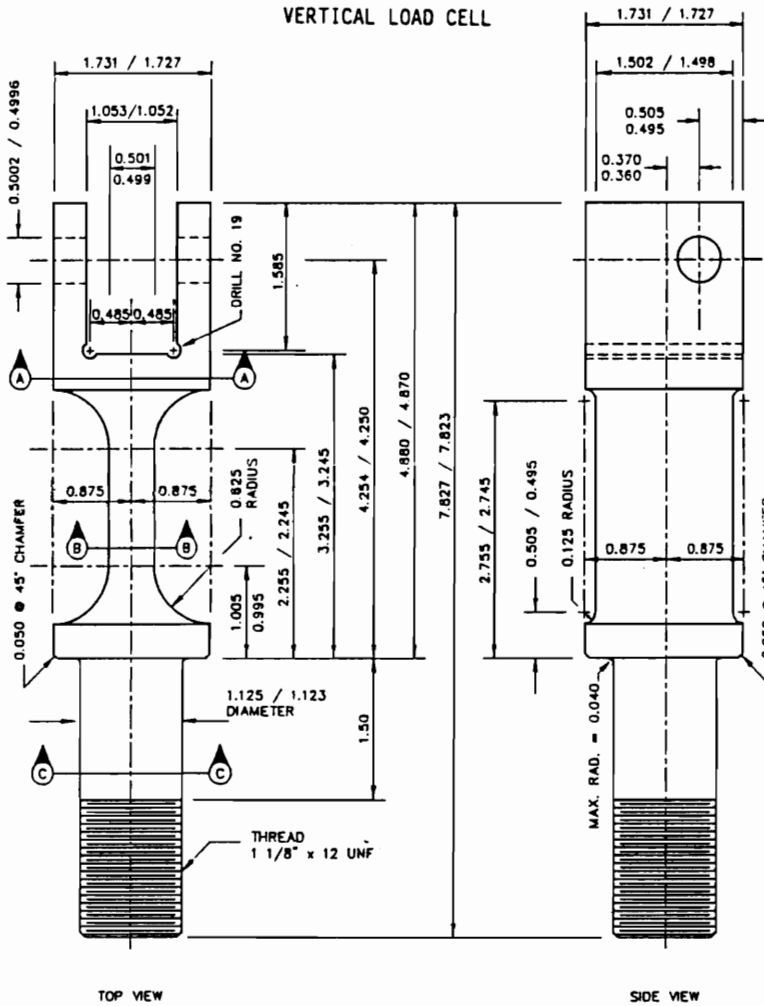
STEEL BEND DETAILS
SCALE: 1" = 1'

CIVIL ENGINEERING DEPARTMENT
VIRGINIA TECH
BLACKSBURG, VIRGINIA 24061
GEOTECHNICAL RESEARCH FACILITY
drawn by: A. L. Senn sheet 11 of 13
2/7/96 scale: AS NOTED



DATE : 1/19/88

VERTICAL LOAD CELL



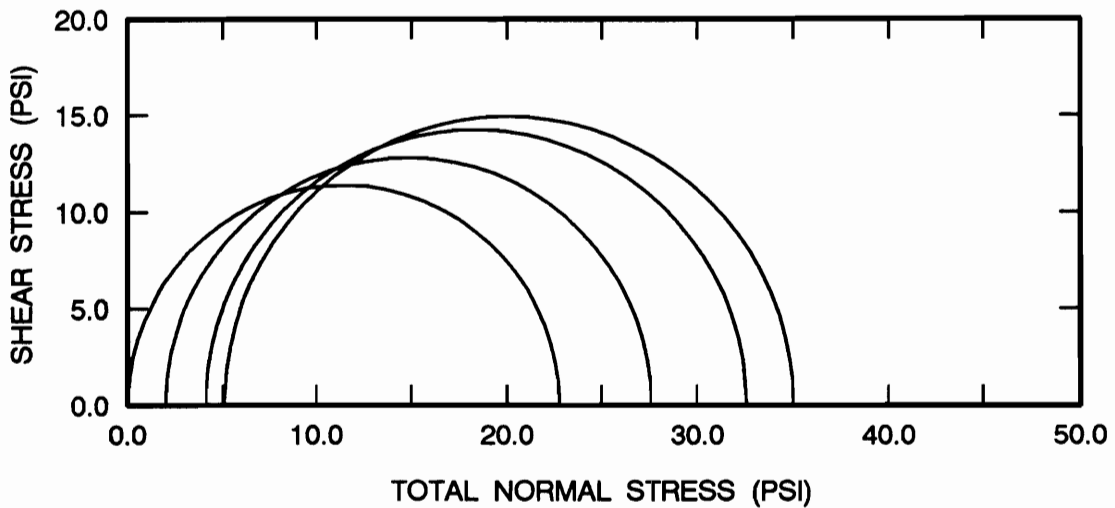
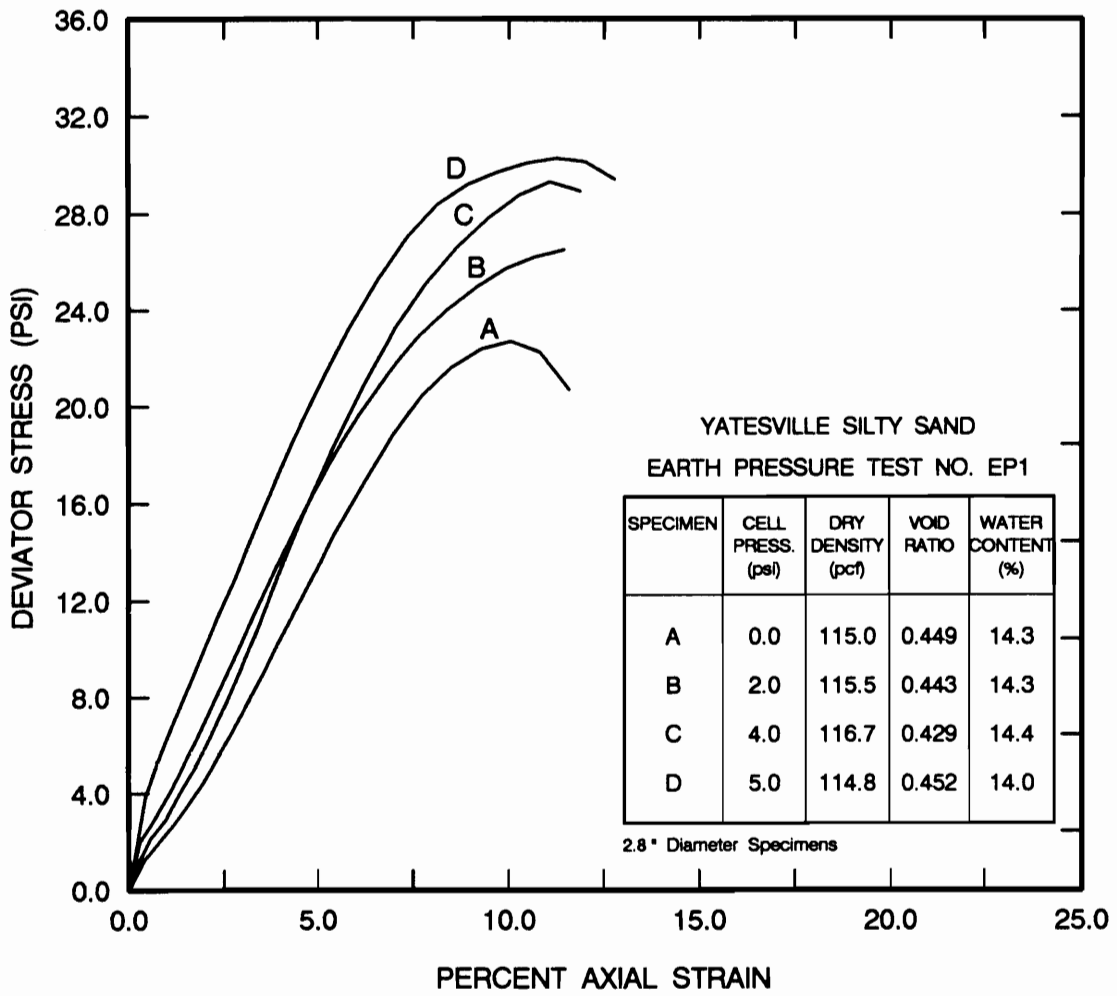
PART NO. : VL2

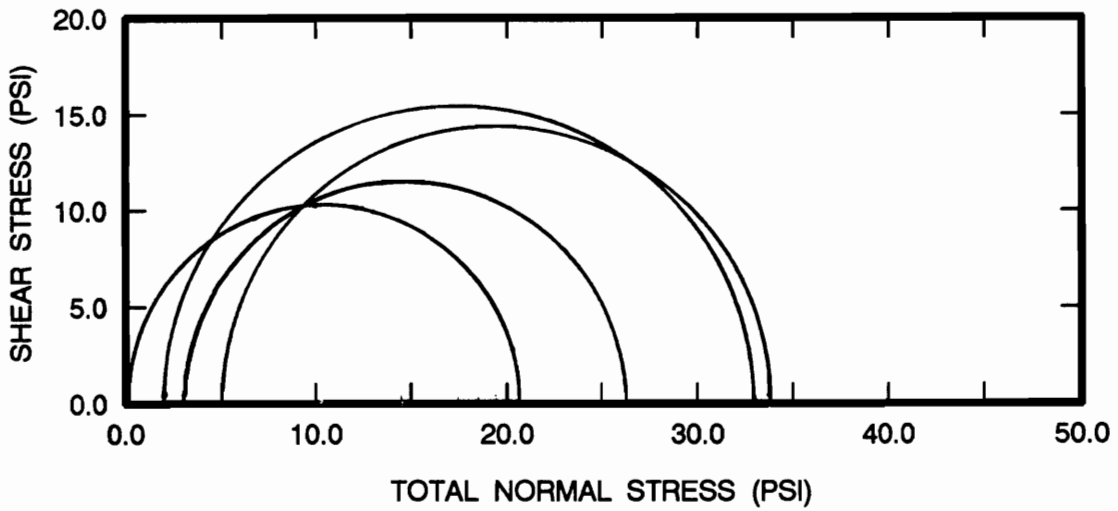
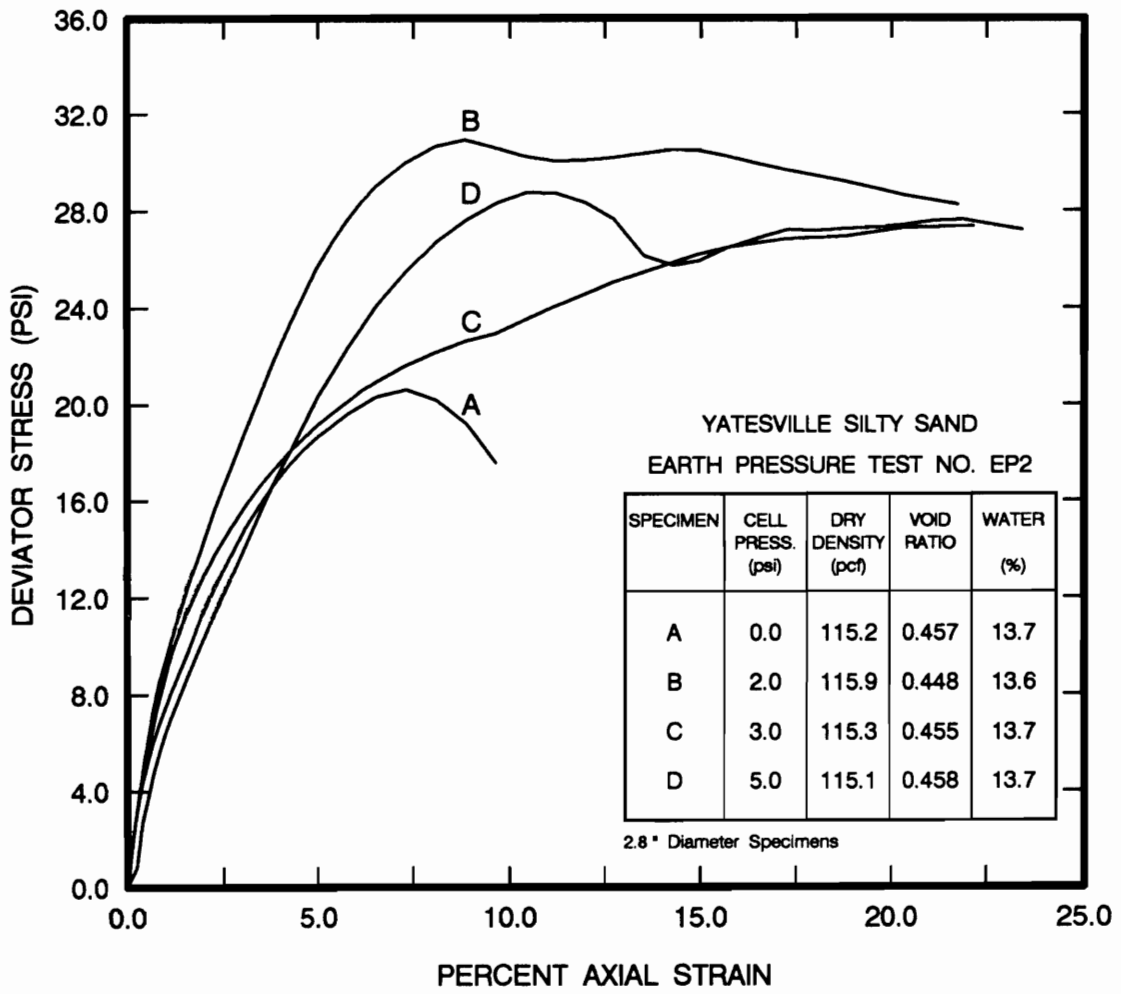
MATERIAL : 17-4 PH STAINLESS STEEL

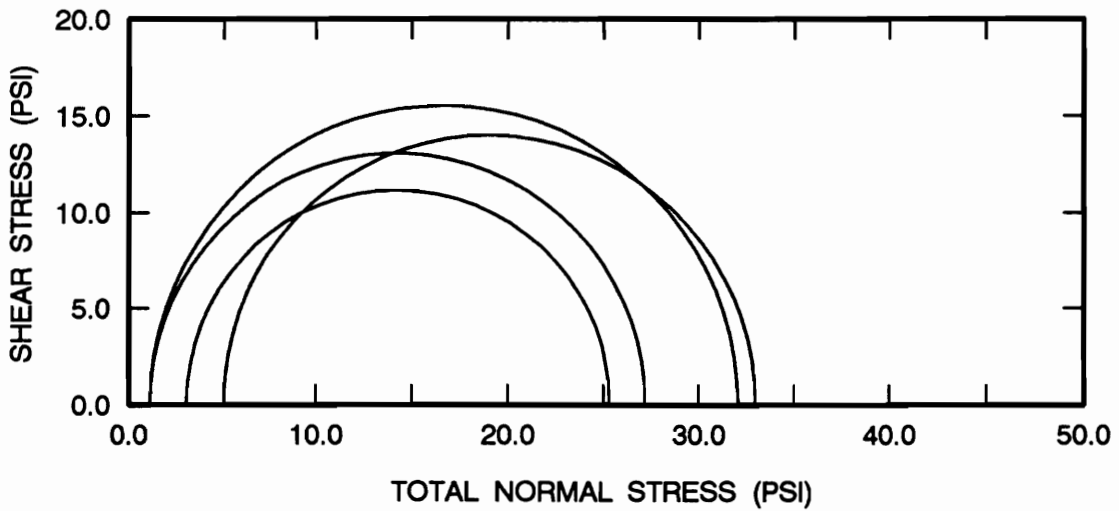
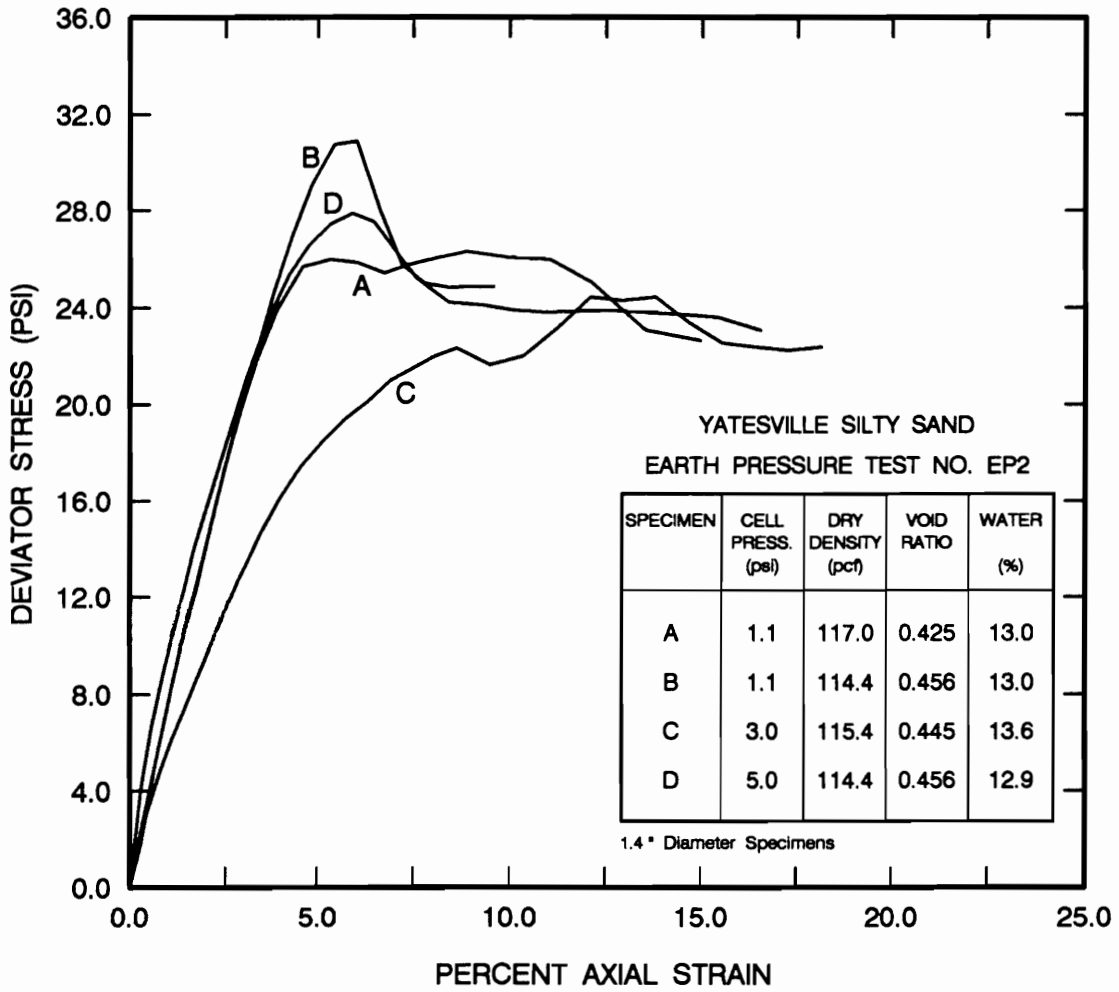
NUMBER OF PIECES : 8

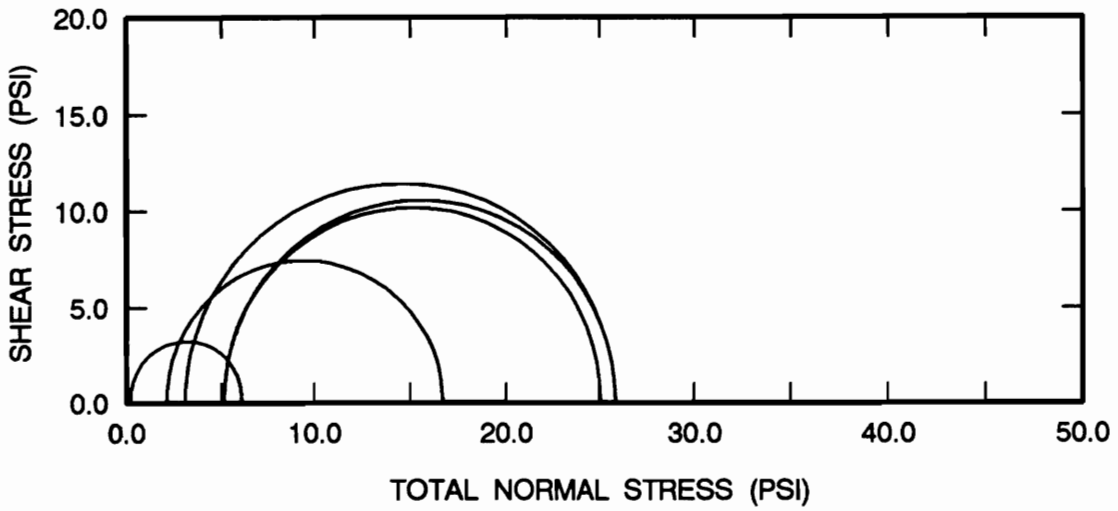
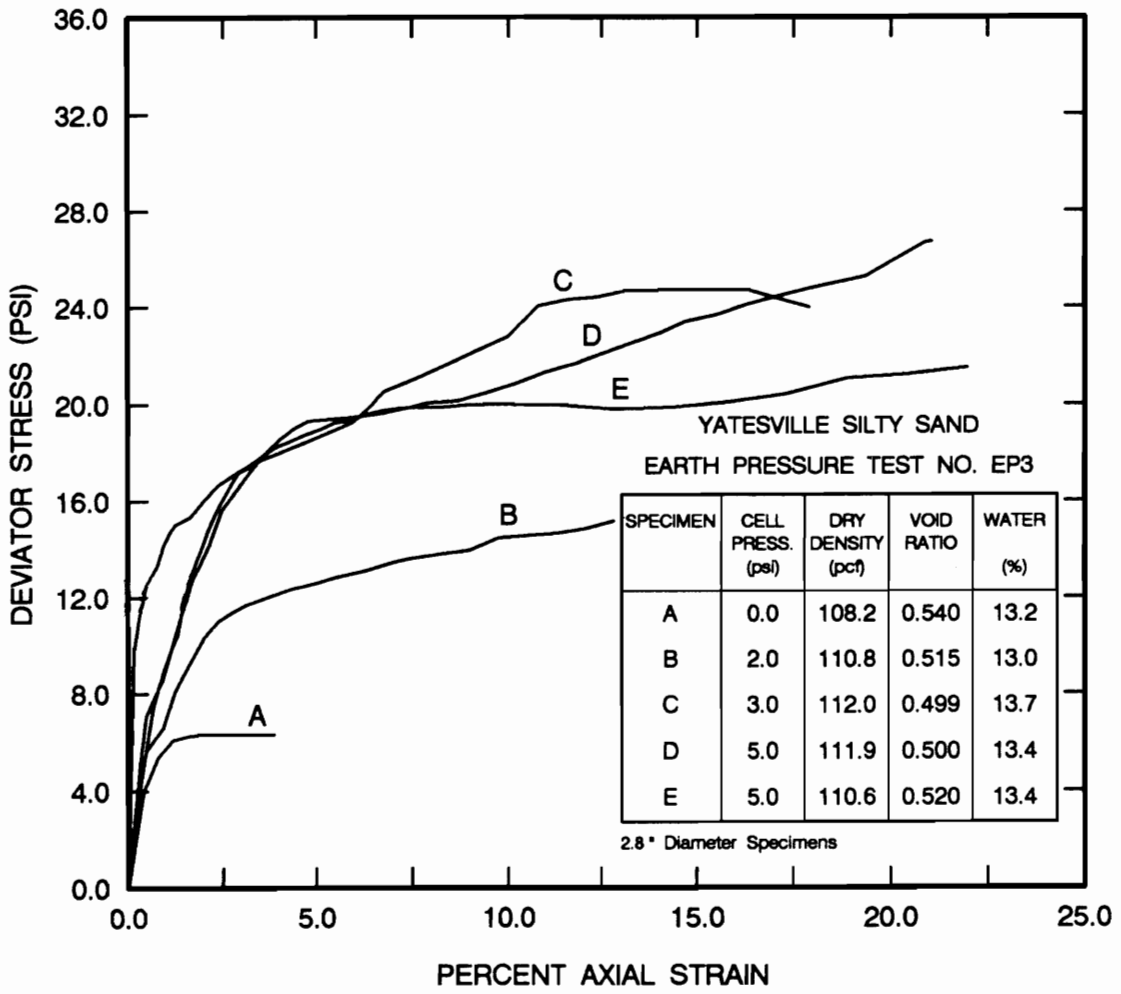
DATE : 2/24/88

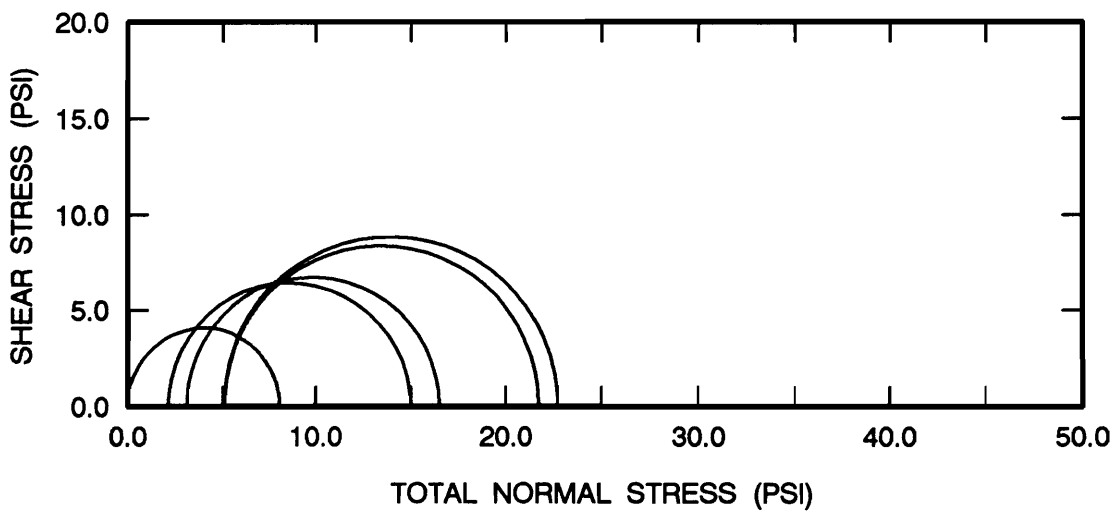
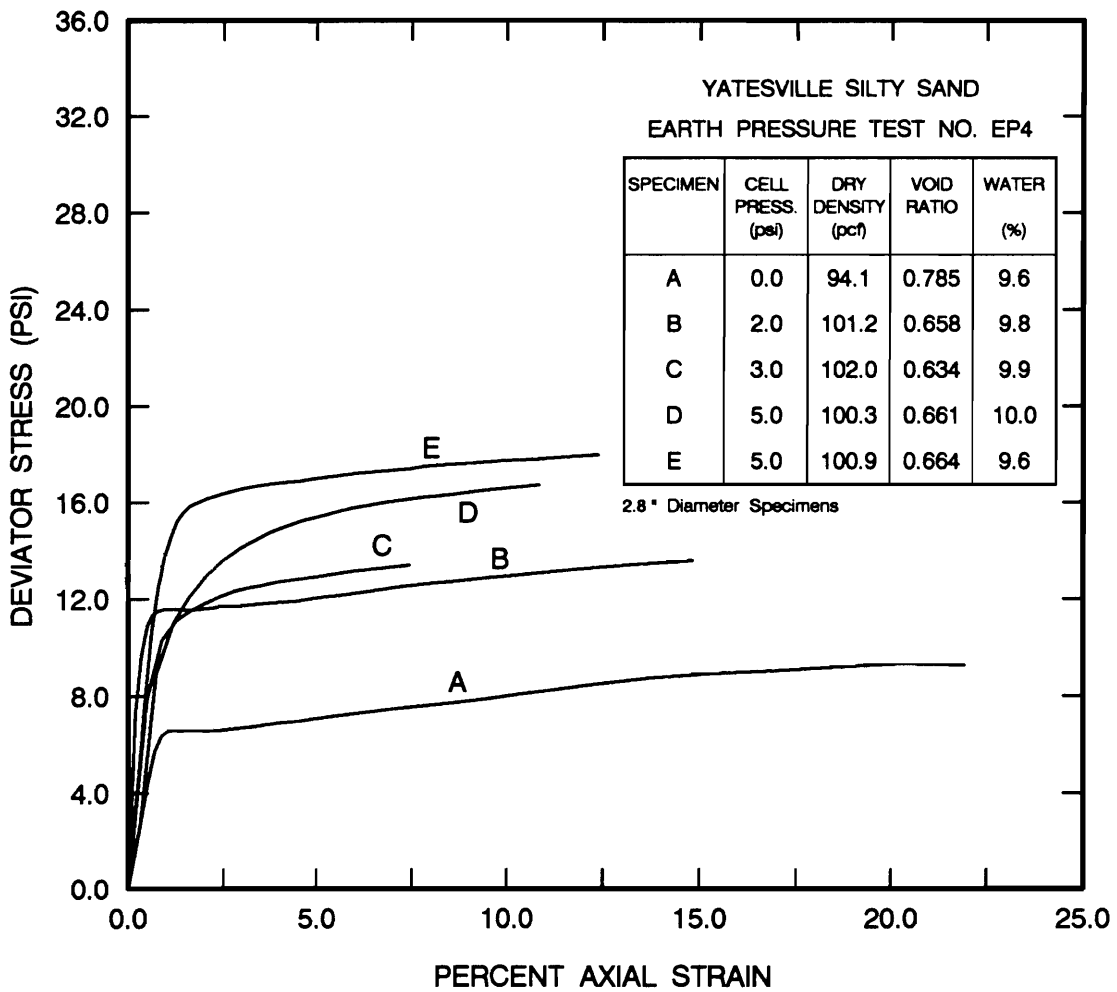
APPENDIX D
RESULTS OF UNCONSOLIDATED-UNDRAINED TRIAXIAL TESTING
ON SAMPLES OF COMPACTED YATESVILLE SILTY SAND











VITA

Allen Lee Sehn was born in Bismarck, North Dakota on December 1, 1958. After graduating from Emmons Central High School in Strasburg, North Dakota, he attended South Dakota School of Mines and Technology where he received the degree of Bachelor of Science in Civil Engineering in 1981 and the degree of Master of Science in Civil Engineering in 1983. He continued his graduate study at Virginia Polytechnic Institute and State University, serving as a graduate research assistant from 1983 through 1987 and as a part-time instructor during 1988 and 1989. He accepted a position as an assistant professor with the Department of Civil Engineering at The University of Akron, beginning January, 1990.

Mr. Sehn is a Registered Professional Engineer in the states of Ohio and Virginia.